Young populations in the large-scale Gould Belt structure

KATIA BIAZZO

INAF – Osservatorio Astronomico di Capodimonte

Outline

- ❑ Introduction
- ❑ Overview of nearby star-forming regions (SFRs)
- ❑ The Gould Belt (GB) in the Orion vicinity
- ❑ Gould Belt surveys
- ❑ Future perspectives

Why young populations?

- Recent Star Formation History/Scenario
- Connection with planet formation
- Isochronal ages and masses
- Connection with the Gould Belt

Why star formation in the solar vicinity (<500 pc)?

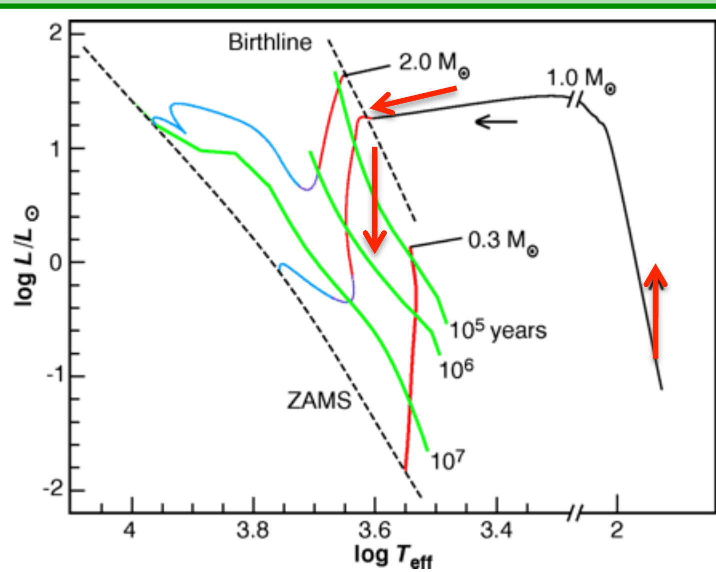
- **Local** star formation in the Galaxy
- **Many stages** of stellar/planetary formation
- **Triggered** and **sequential** star formation

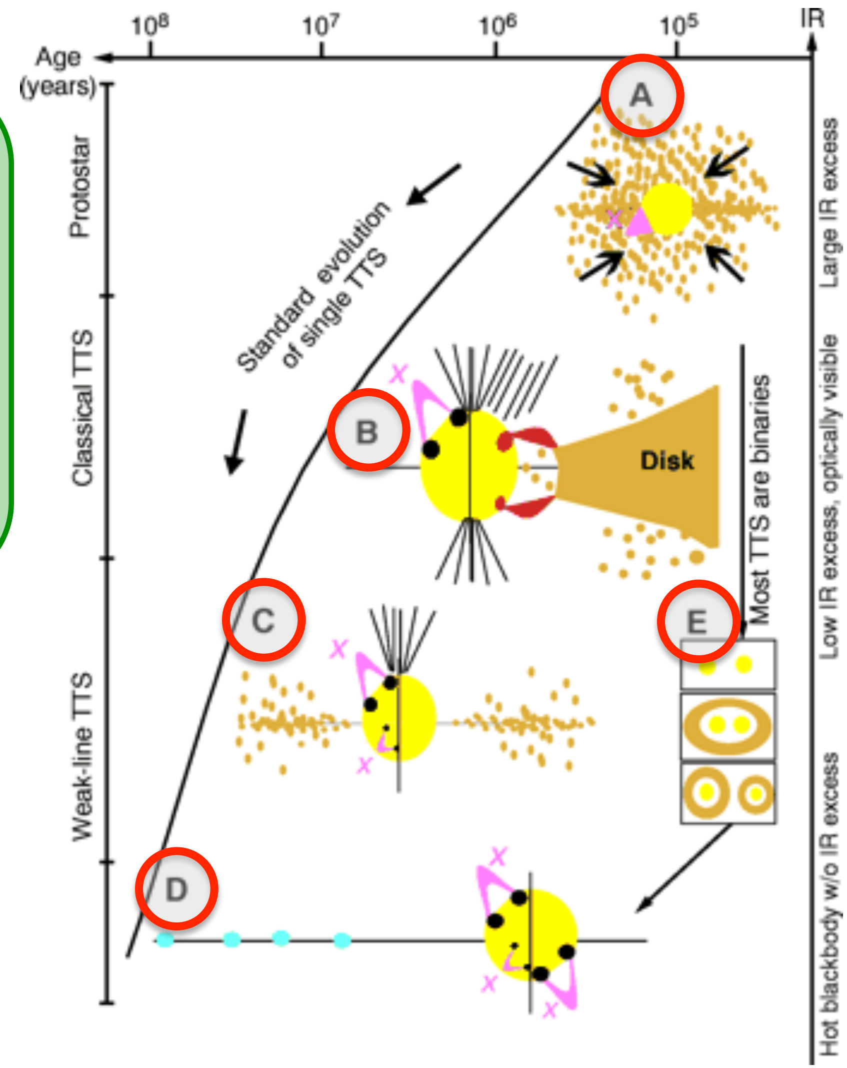
Why star formation of low-mass stars?

- **Numerous**
- **Less problems** in model atmospheres
- **More** suitable **lines** for abundances
- **Low rotation**
- Good candidates for **exo-planet** research

Schematical model

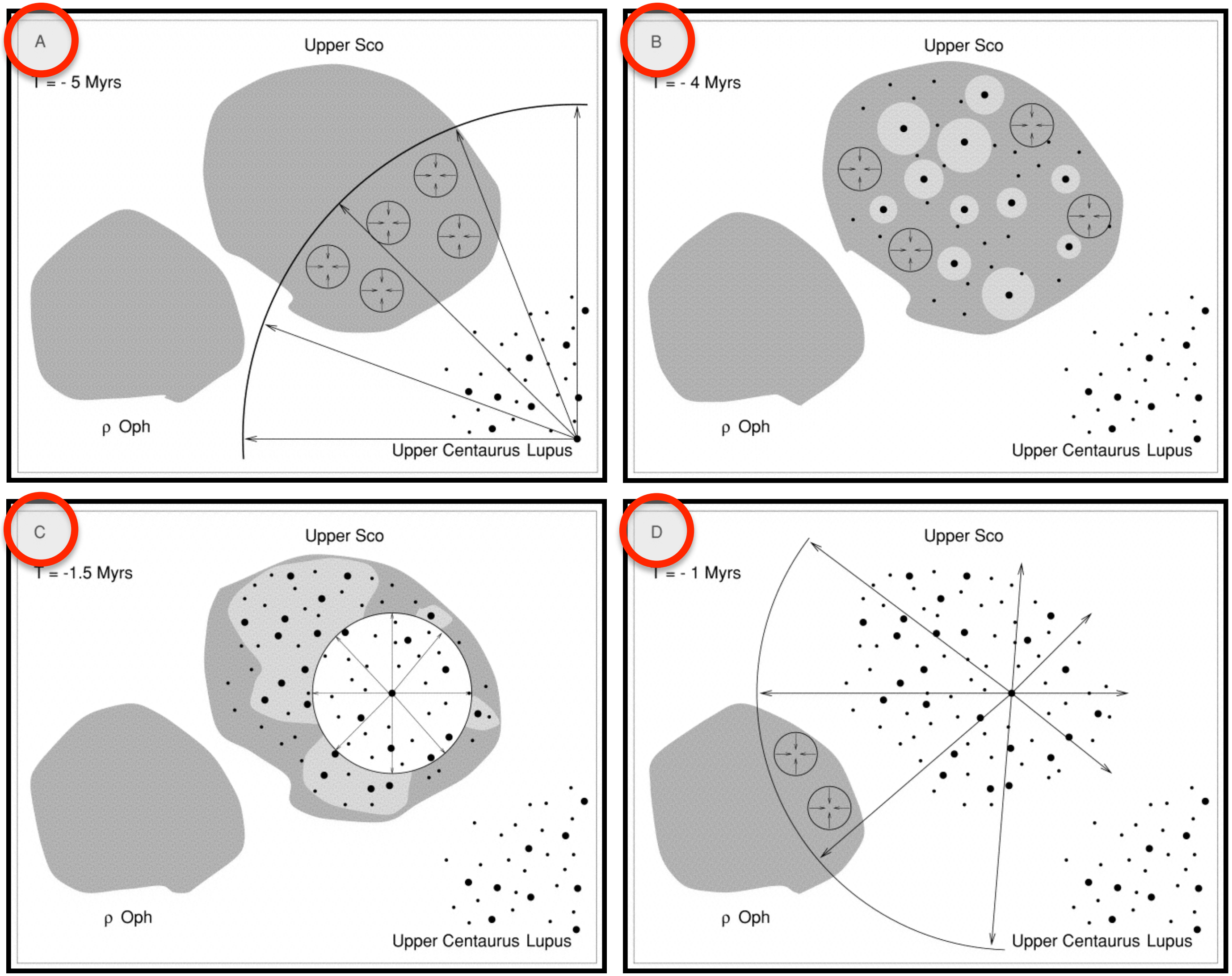
- A : embedded protostar accreting cloud material (class I)
- B : protostar with circumstellar disk (class II, cTTS)
- C : star with accretion coming to a halt (class III, wTTS)
- D : star with possibly having orbiting planets (pTTS, sun-like)
- E : binary stars (capture, disk fragmentation, collapsing filamentary cloud)





Neuhäuser (1997)

Schematic view



Preibisch & Mamajek (2008)

Age (Erickson et al. 2011, Pecaut et al. 2012):

- UCL: 16 Myr
- US: 11 Myr
- ρ Oph: 1-3 Myr

Where are located?
SFRs, OB stars & Gould Belt origin, nature, position
Presence of young low-mass stars in the GB

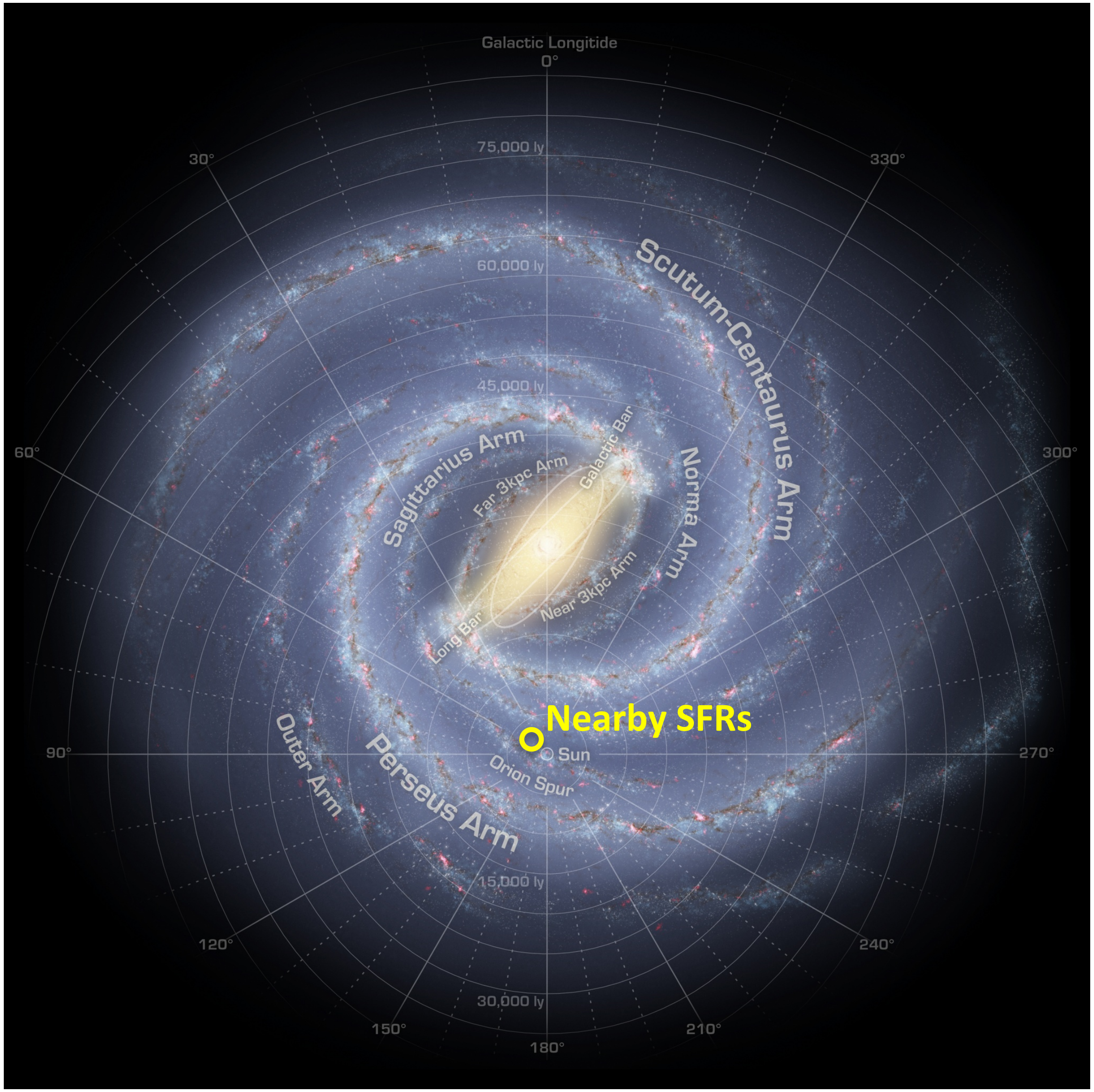
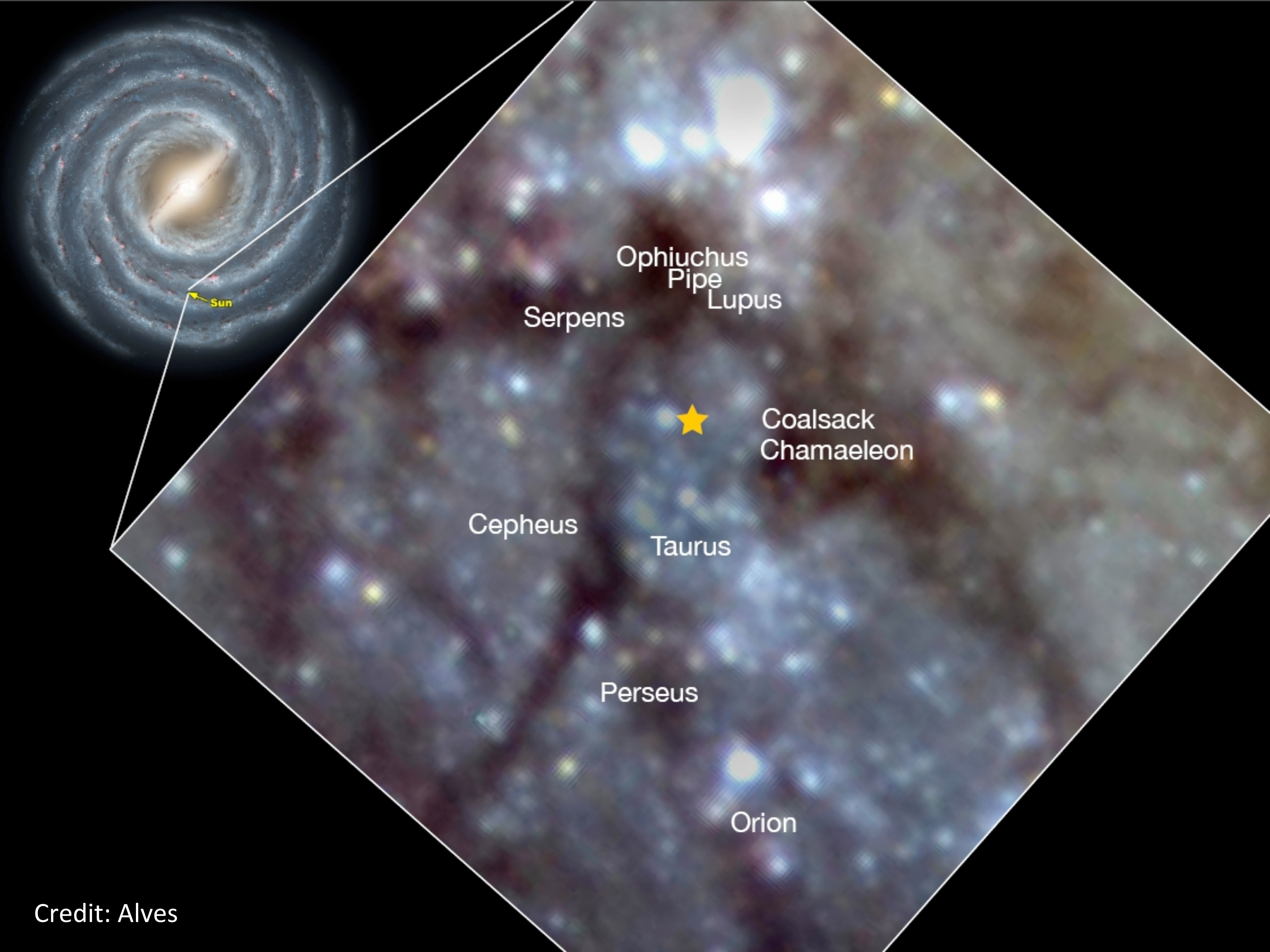
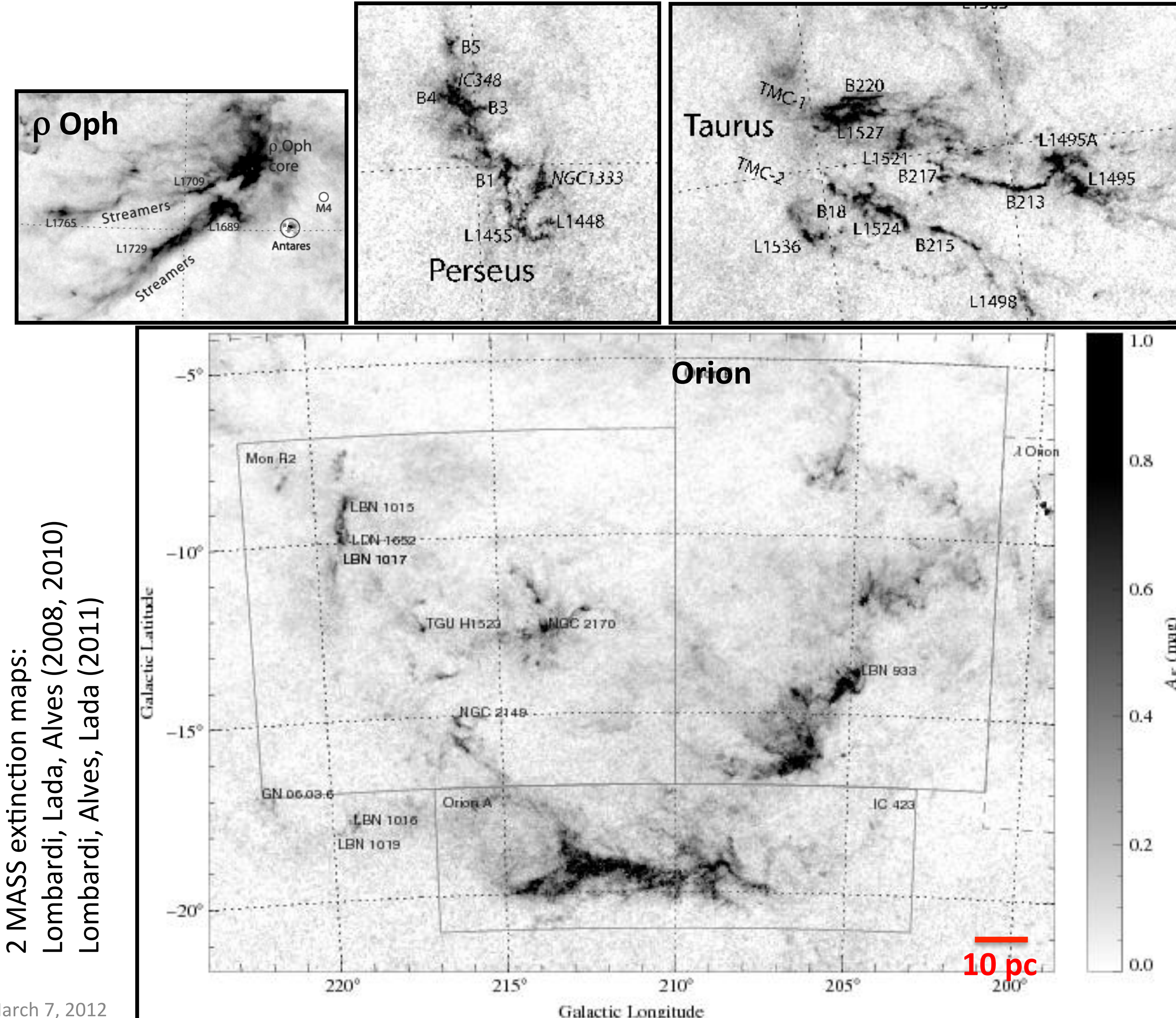


Illustration credit: Hurt
Survey credit: GLIMPSE



Credit: Alves



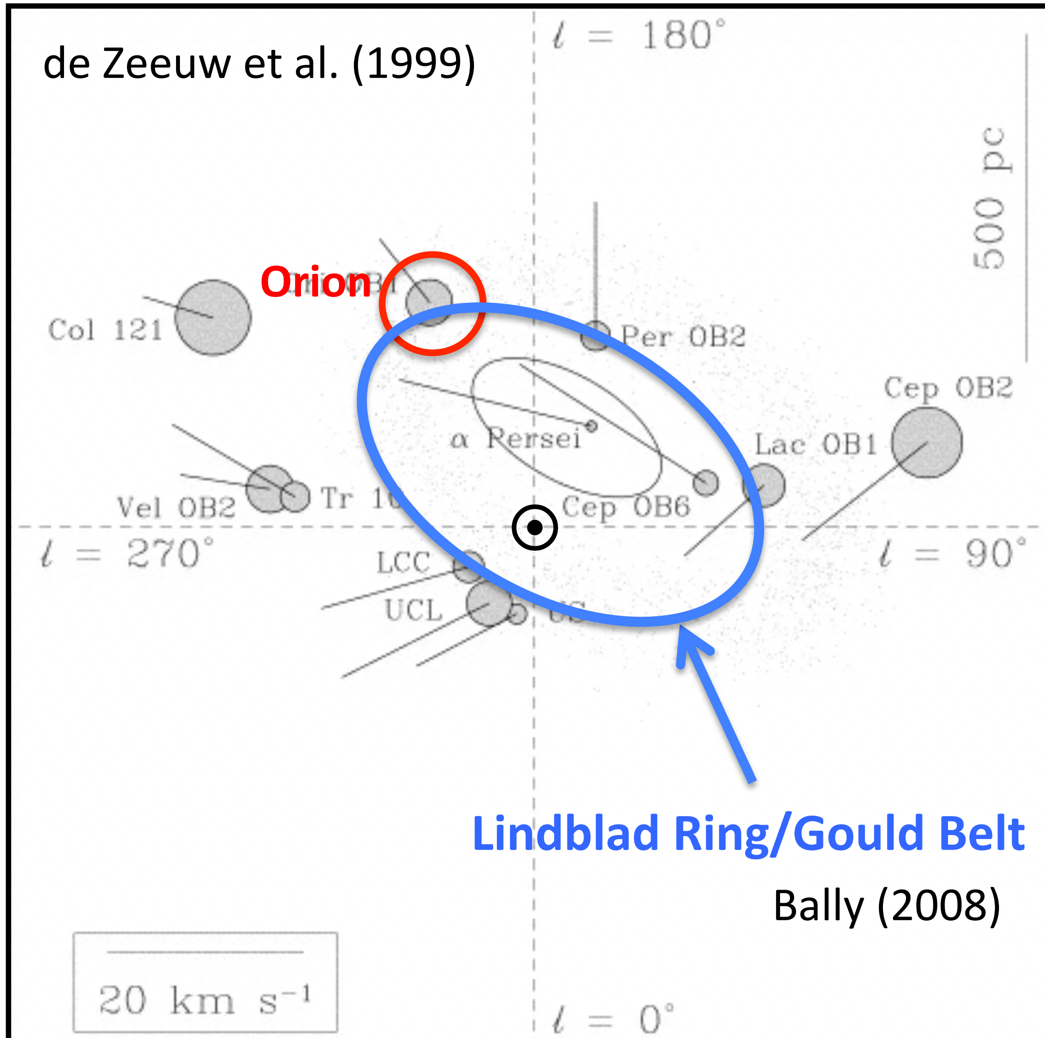
Credit: Alves

2 MASS extinction maps:
Lombardi, Lada, Alves (2008, 2010)
Lombardi, Alves, Lada (2011)

Summary Historical Overview
The GB Geometry

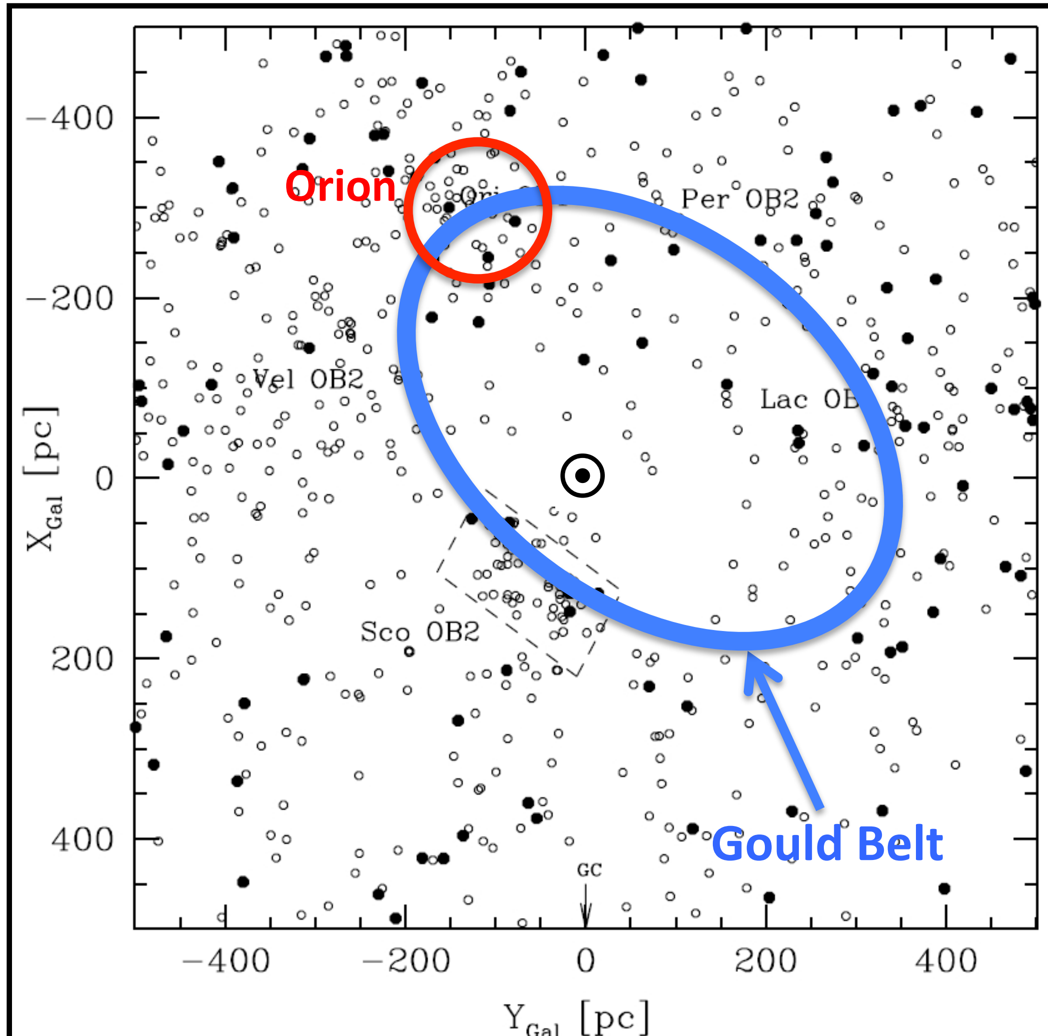
- ❑ Sir John Herschel (1847): distribution of bright stars **asymmetric**
- ❑ In 1874 Benjamin Gould: Belt **orientation** with respect to the Galactic Plane
- ❑ Lindblad (1967): Belt **rotation** (containing interstellar clouds) and **expanding** HI ring
- ❑ Taylor et al. (1987): H_2 **complexes** (e.g., Orion and Ophiuchus) and dark clouds are related to the Belt and participate to the expansion
- ❑ Comerón et al. (1994): 40-50% of the young massive stars within 450 pc belong to the Belt; Torres et al. (2000): new *Hipparcos* data bring this fraction to 60-66% for **high-mass stars** within 600 pc and age of 30-60 Myr; 3D reddening maps (Gontcharov 2010) and CO maps (Dame et al. 2001): most of the molecular clouds within 1 kpc follow the GB pattern
- ❑ Guillout et al. (1998a): Young (30-80 Myr) lithium-rich **low-mass stars** with active coronae are X-ray sources tracing the 'Gould Disk'
- ❑ Lindblad et al. (1997): the rotation may explain the persistence of a **flat disk**
- ❑ Comerón (1999): the rotation axis is **not perpendicular** to the Galactic plane
- ❑ Perrot & Grenier (2003): new estimates of geometrical structure and velocity fields

Young associations projected onto the Galactic Plane

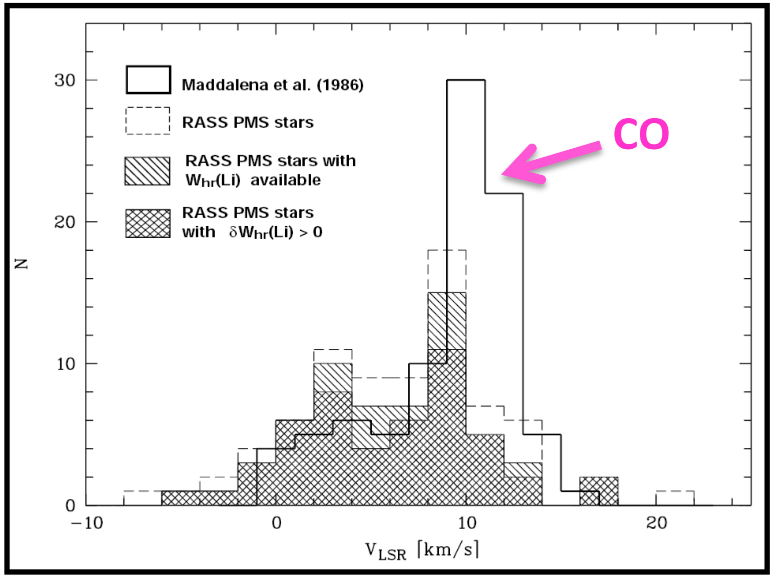


O-B stars as looking down upon the Galactic Disk

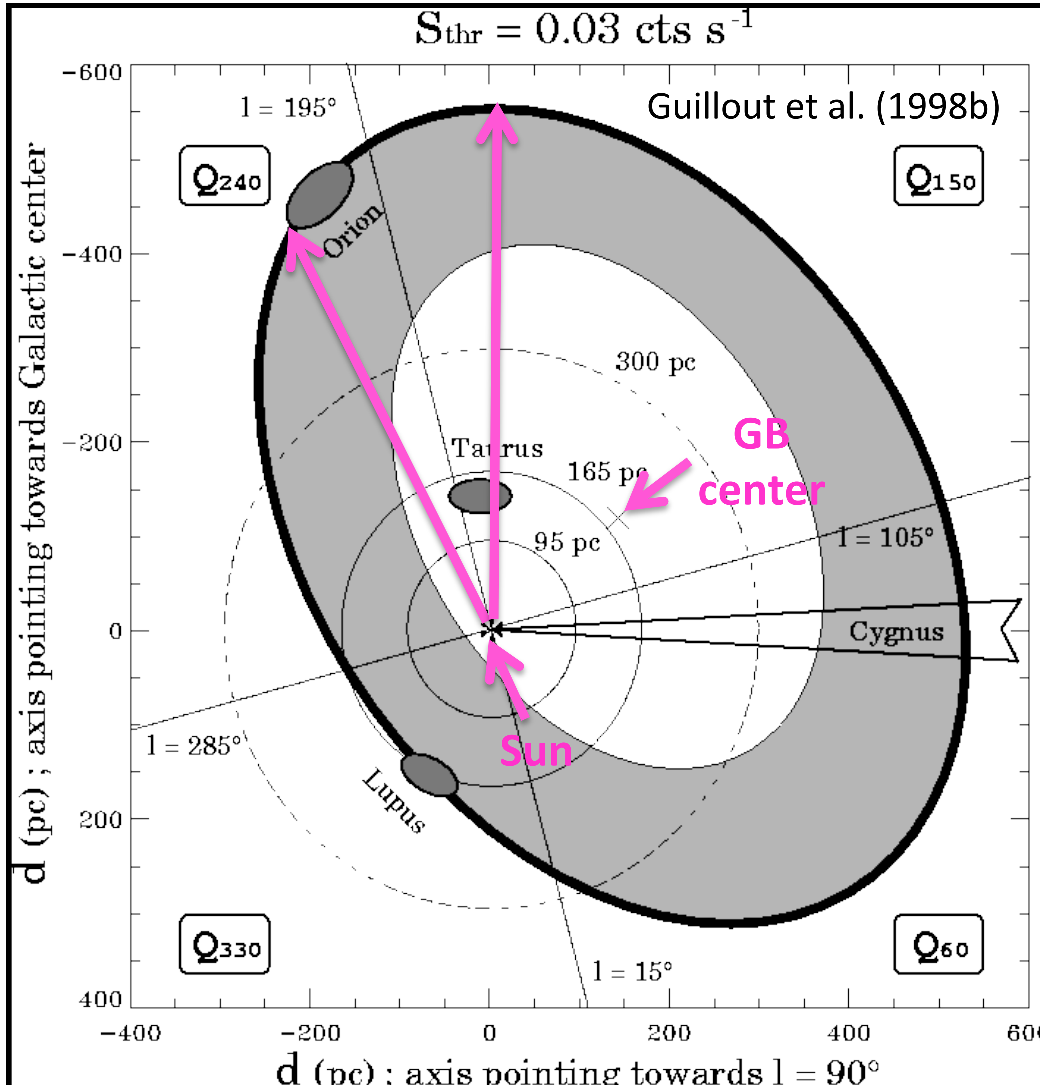
Preibisch & Mamajek (2008):
- Dots: ≤ B0
- Circles: B1-B2



The "Gould Disk"



Alcalá et al. (2000)

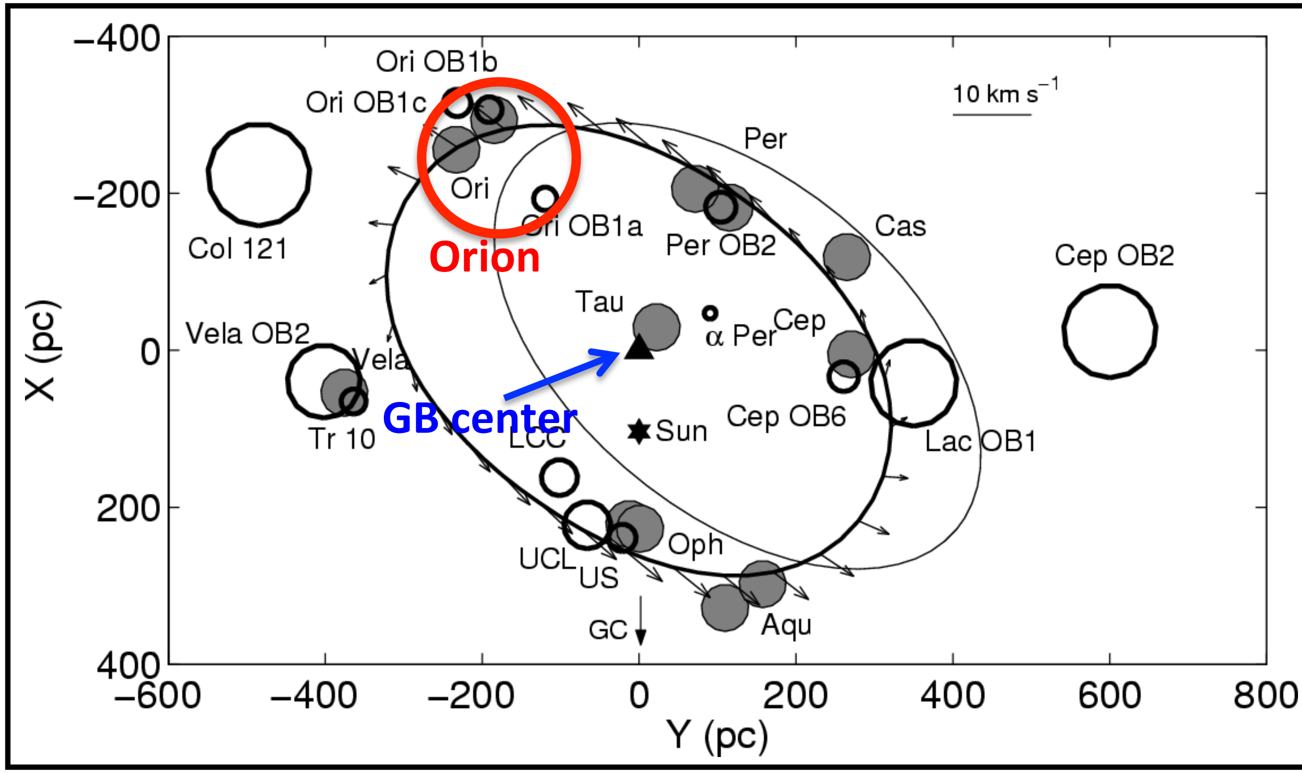


Credit: Alcalá

Present/past position of the GB projected on the Galactic Plane

Perrot & Grenier (2003):

- Major semi-axis: 354 pc
- Minor semi-axis: 232 pc
- Thickness: 60 pc
- Inclination: 17°
- d_{center}: 104 pc
- l_{center}≈150°-180°



: nearby associations

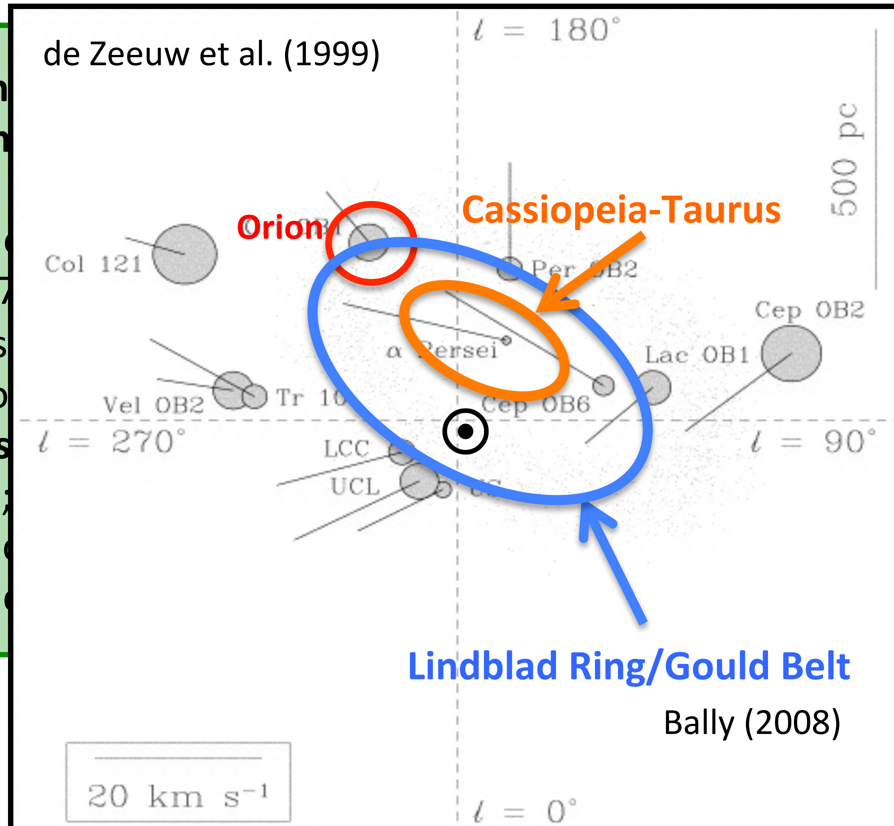
: H_2 clouds

Summary Historical Overview
The GB Origin

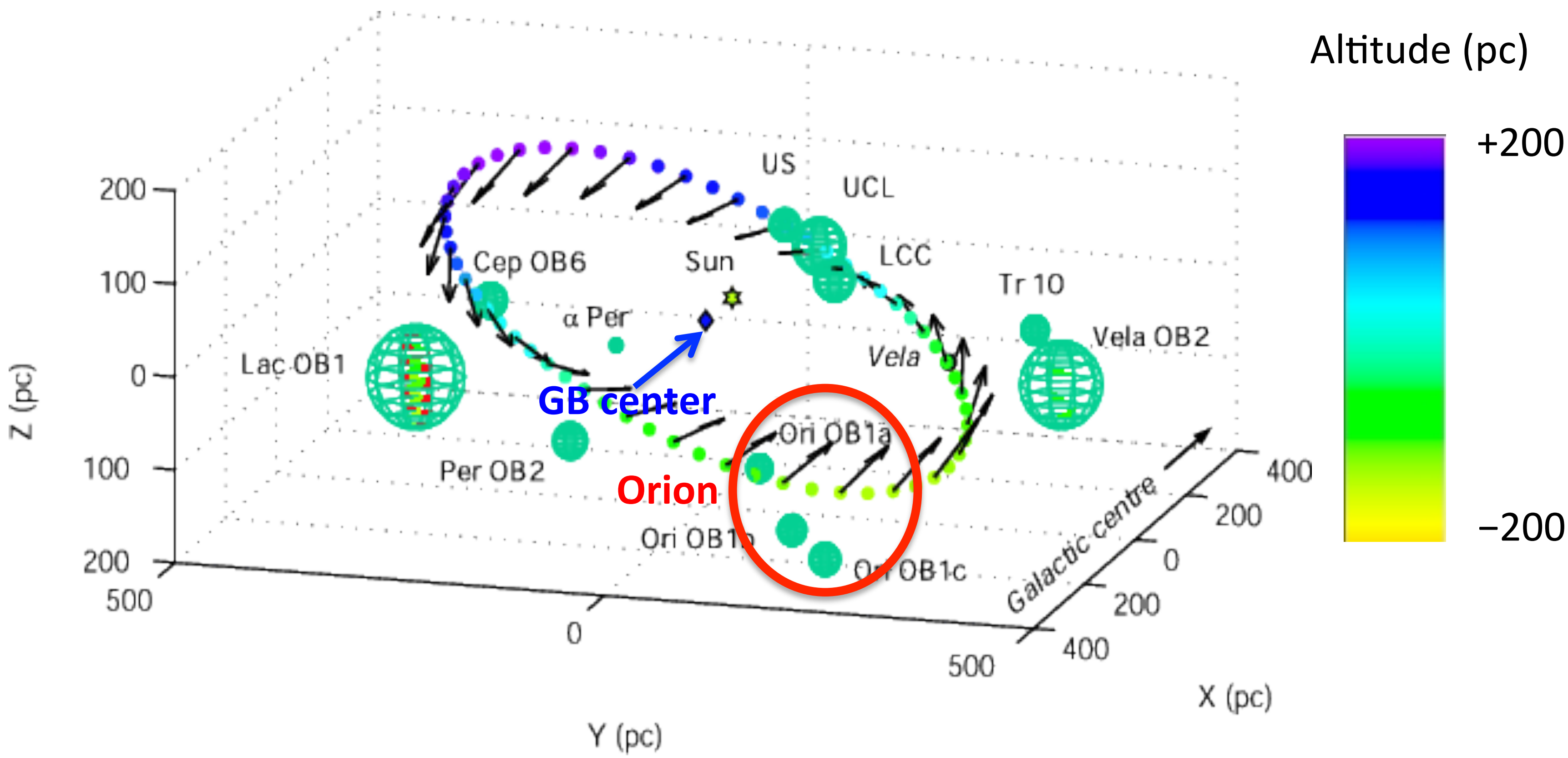
- **Expansion** from the Cassiopeia-Taurus center (Blaauw 1991)
- **Oblique impact** of a high-velocity HI cloud on the Galactic disk (Comerón & Torra 1992)
- Feedback effects of **supernova explosions** on the interstellar medium (Pöppel 1997)
- 2D expansion, within the Galactic plane, of an initially circular **shock wave** (Olano 1982) or of a superbubble (Moreno et al. 1999)
- 3D **expansion** of a **superbubble** in a uniform or non uniform medium (Olano 2001; Perrot et al. 2003)
- High-speed, off-center **collisions** between giant molecular clouds and dark matter clumps orbiting the Galaxy (Bekki 2009)

Summary Historical Overview
The GB Origin

- **Expansion**
- **Oblique in** (Comerón &
- Feedback (Pöppel 1997 ... medium
- 2D expans ... **shock wave** (Olano
- [3D](#) **expans** ... medium (Olano 2001;
- High-speed ... uds and dark matter

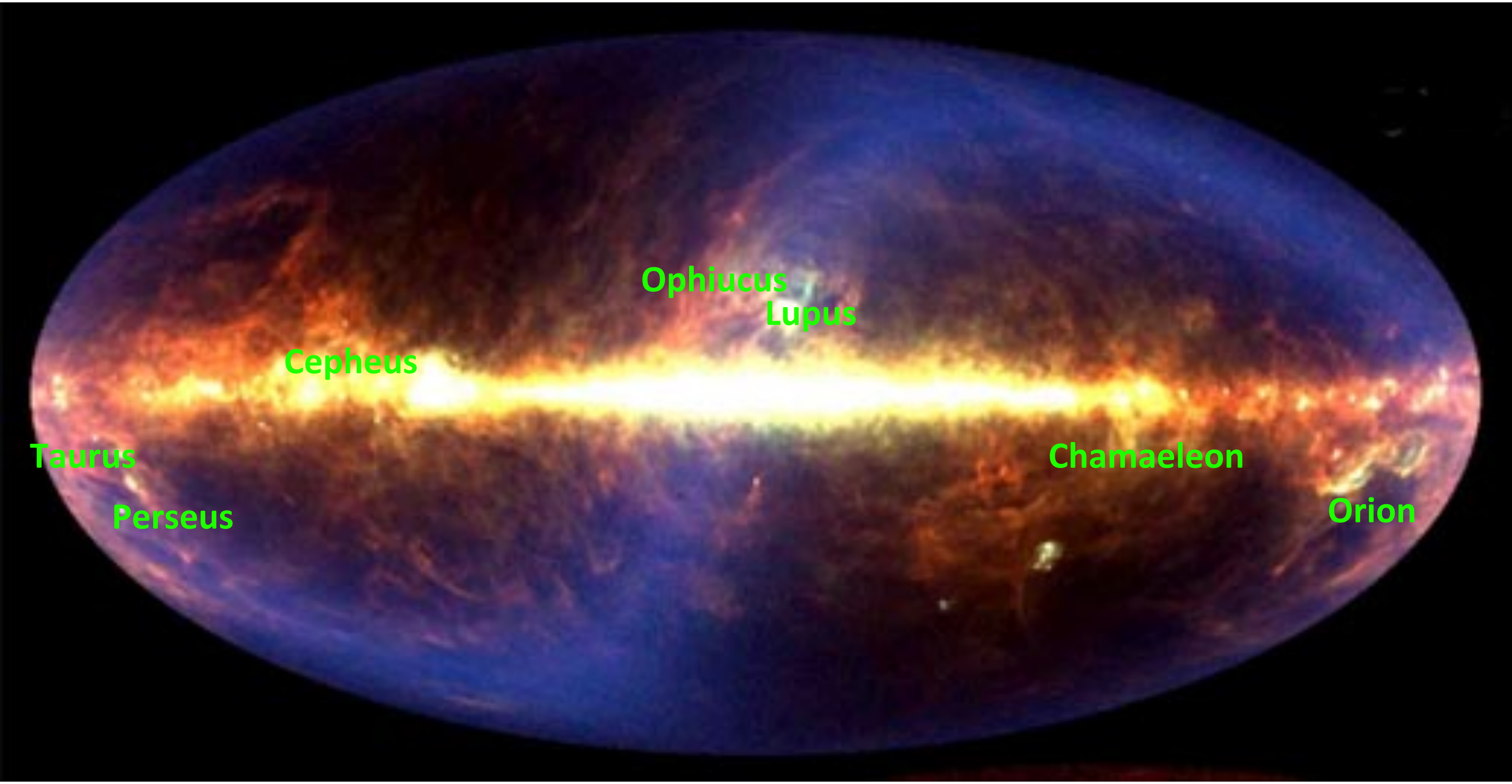


3D present position of the GB and its velocity fields



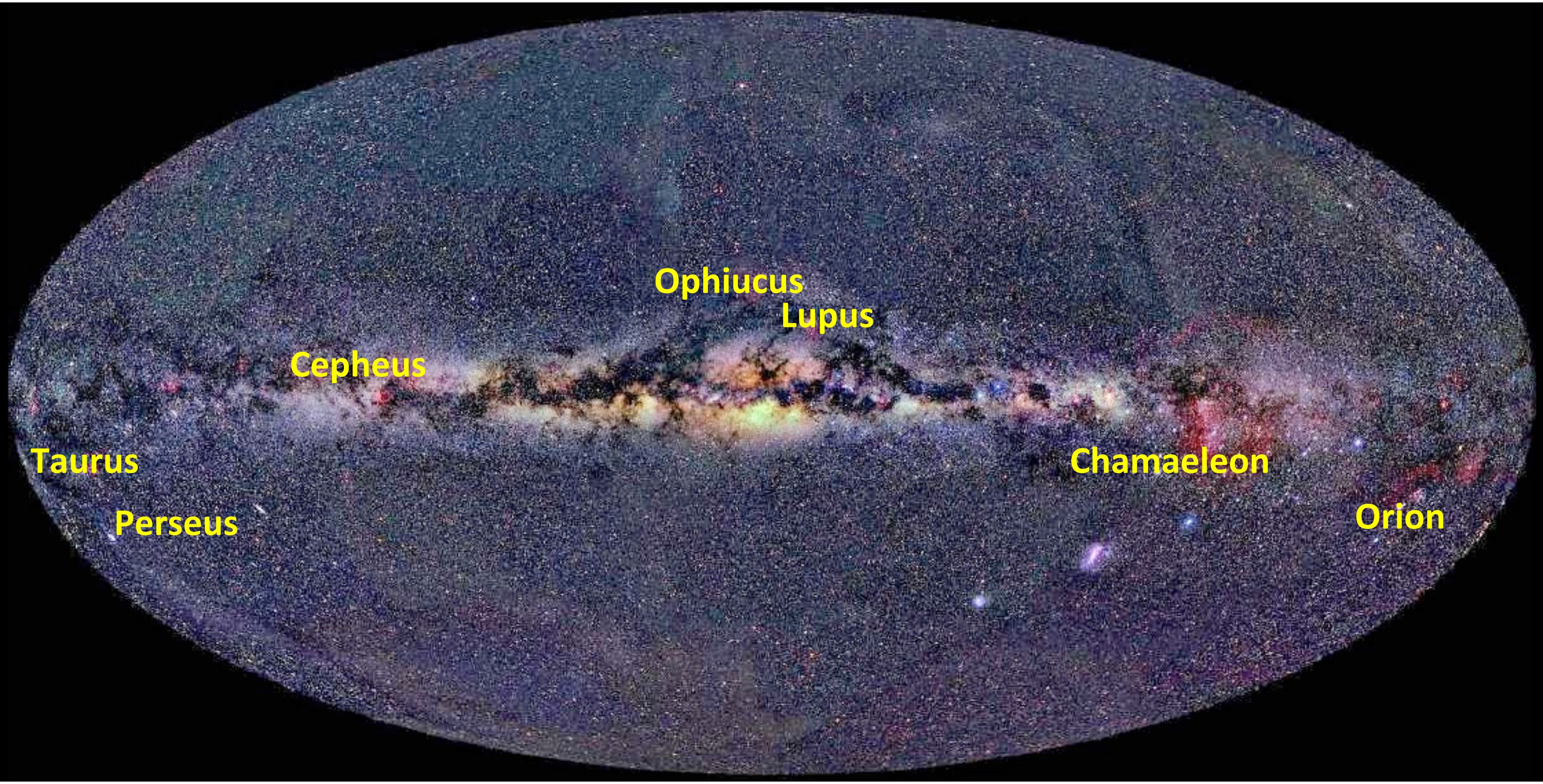
Perrot & Grenier (2003)

InfraRed



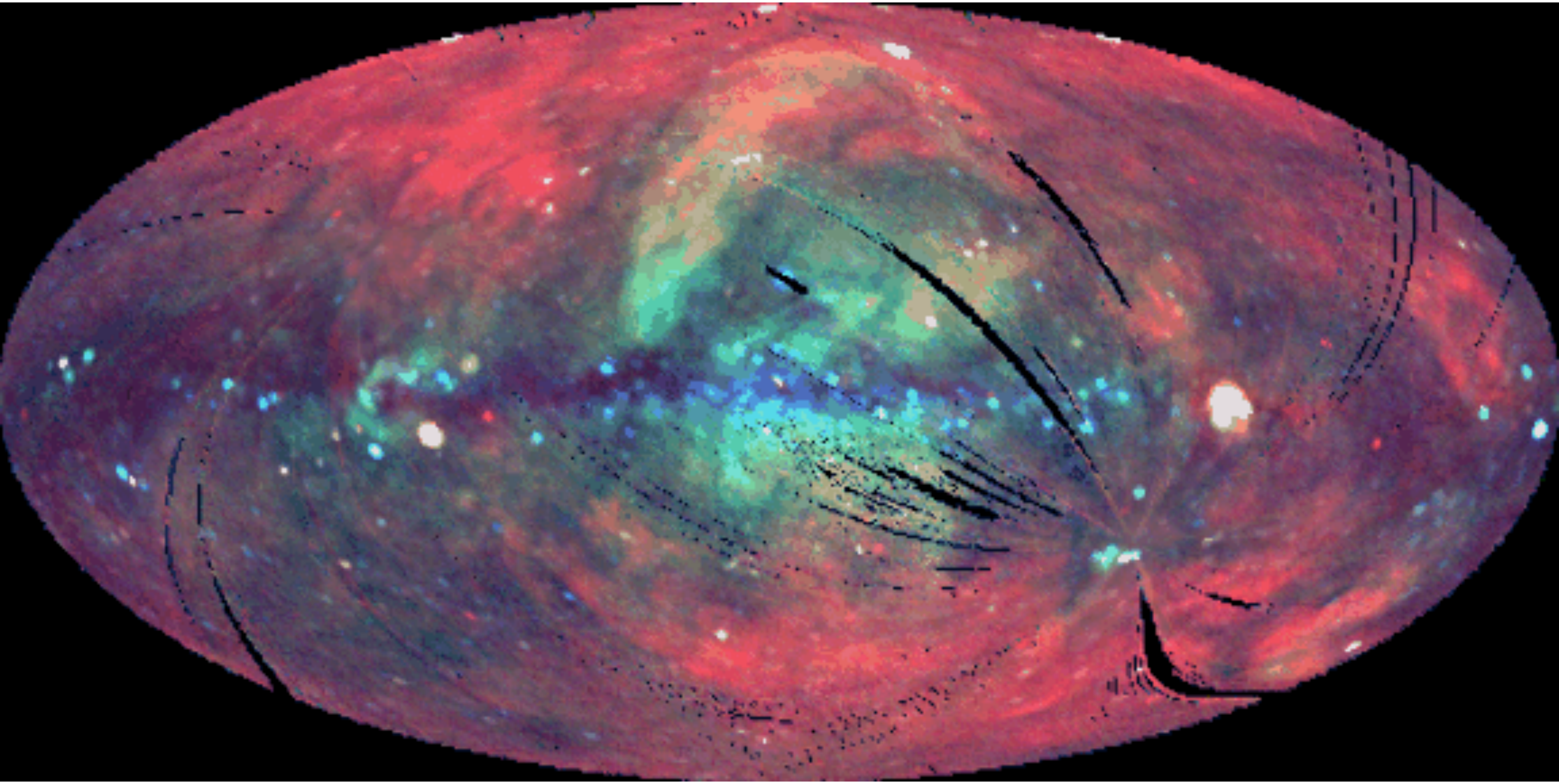
IRAS@12,60,100 μm image

Optical



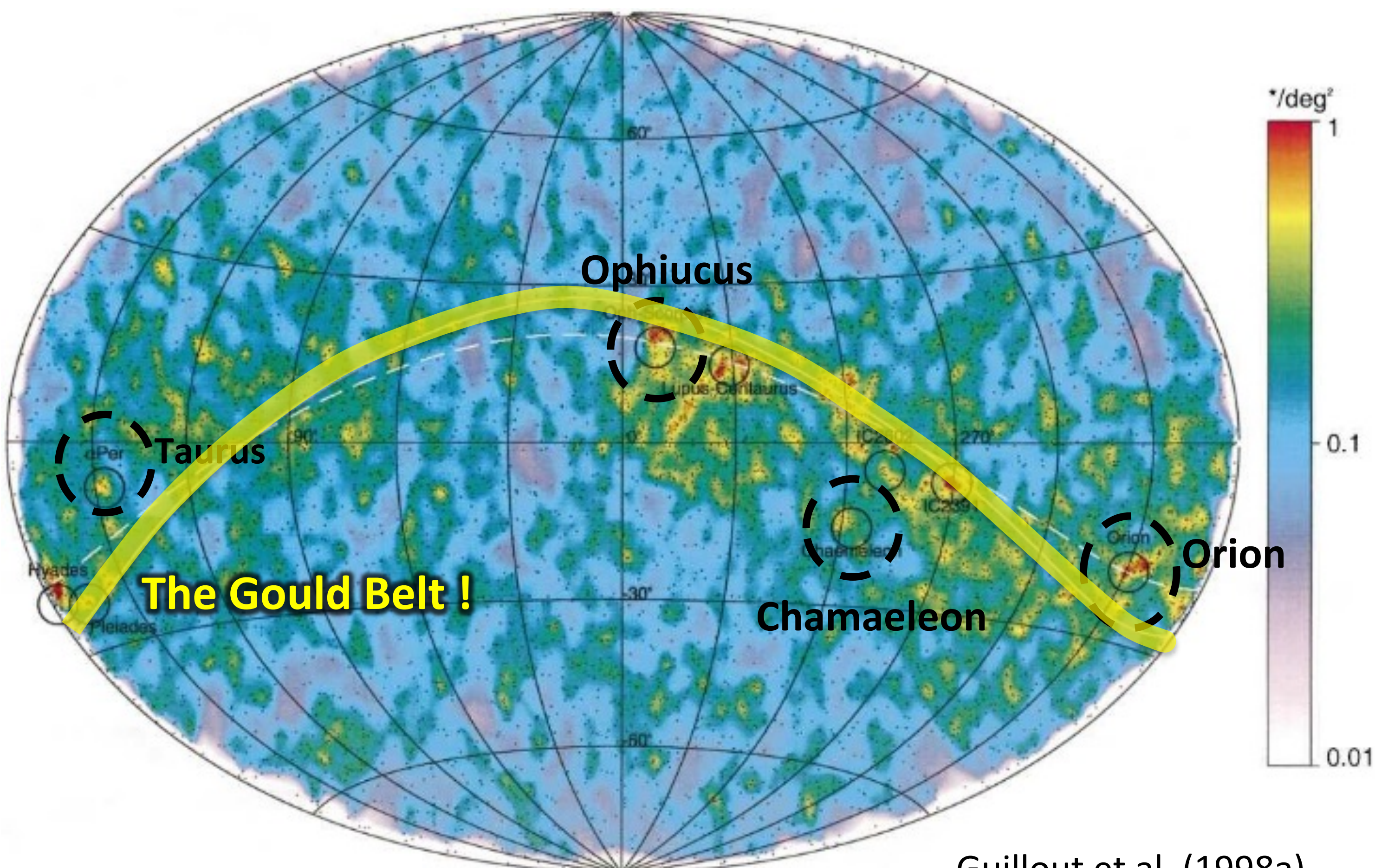
Credit: Mellinger

X-ray



ROSAT@0.25,0.75,1.5 keV

Cross correlating the RASS & Tycho catalogues…



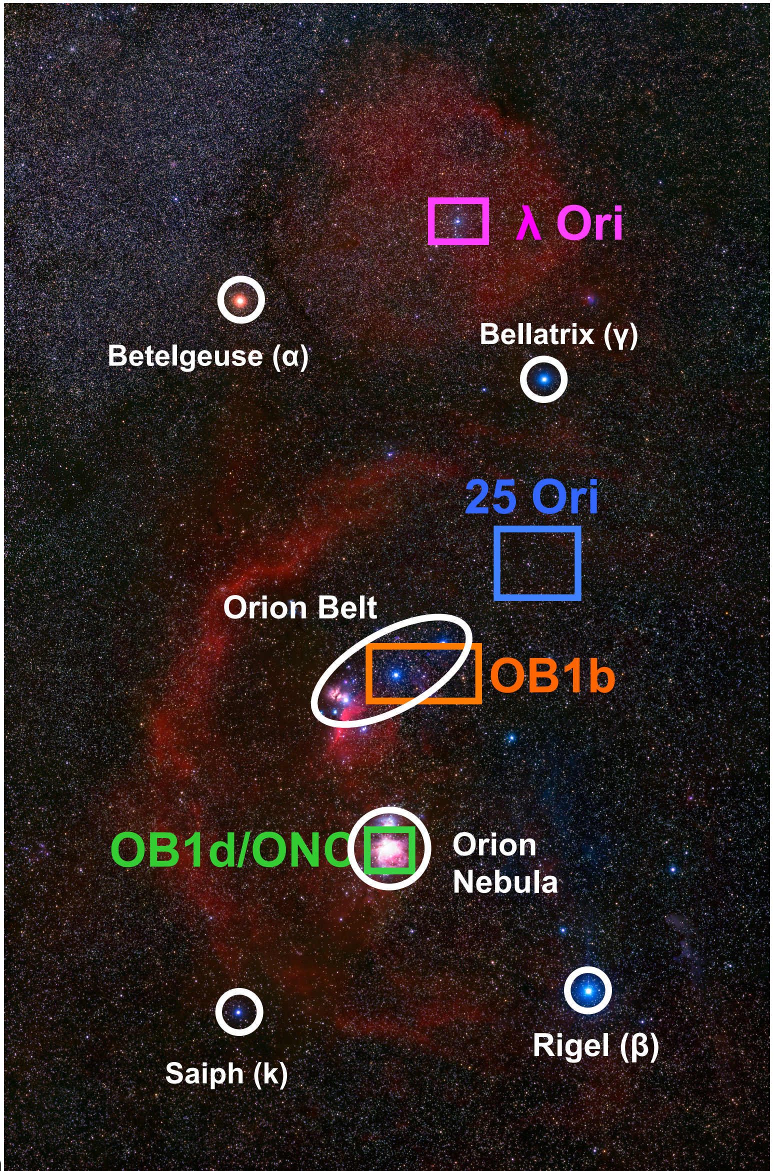
Guillout et al. (1998a)

The Gould Belt in the Orion vicinity

The on-cloud population

The off-cloud population

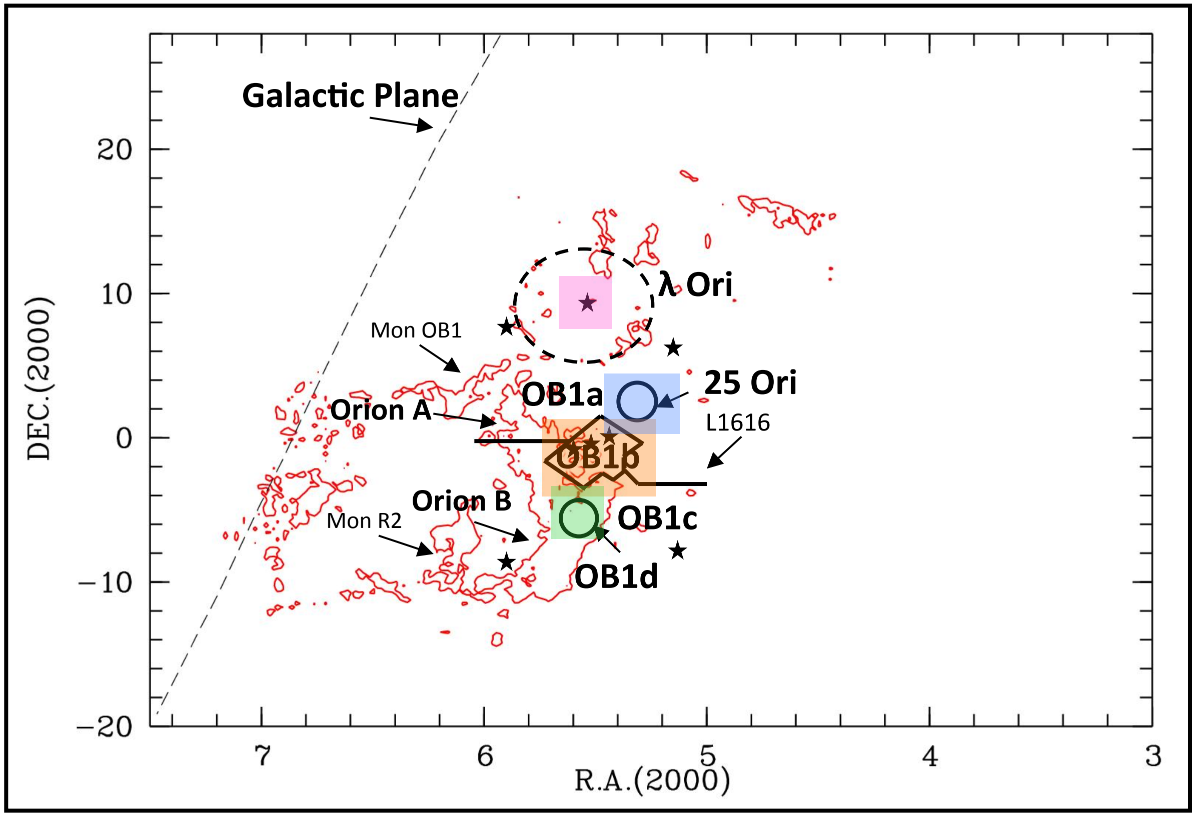
Photograph in visible light by Wei-Hao Wang, University of Hawaii



Properties and position

- **Observations** (≈50 stars): FLAMES/UVES@VLT (R=47000)
- **Analysis**:
  - Stellar parameters (T_{eff}, logg)
  - Radial velocity
  - Abundance: MOOG code (Sneden 1973) + ATLAS9 (Kurucz 1993) or GAIA (Brott & Hauschildt, priv. comm.) model atmospheres

Properties and position

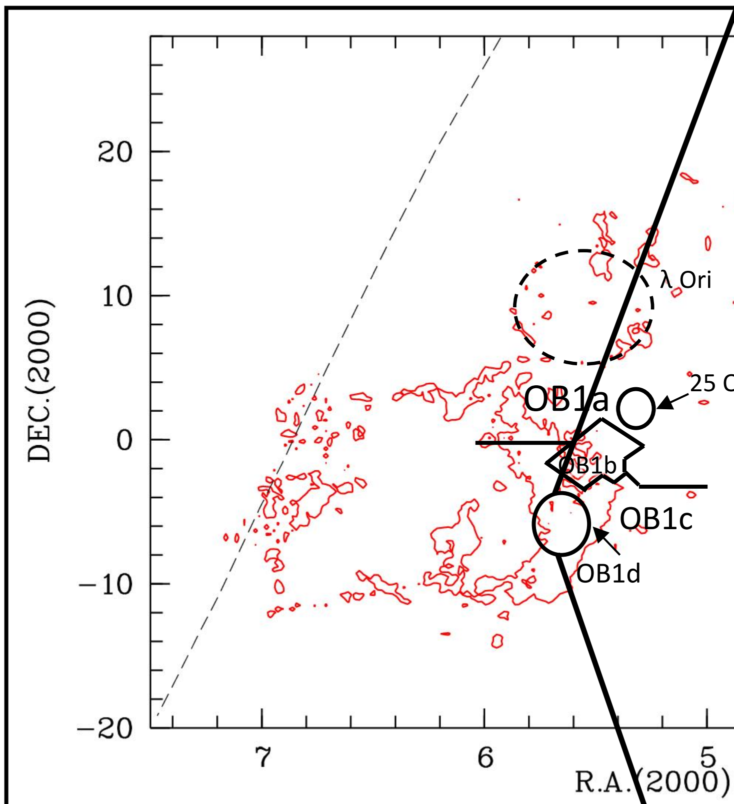


CO map (Maddalena et al. 1986)

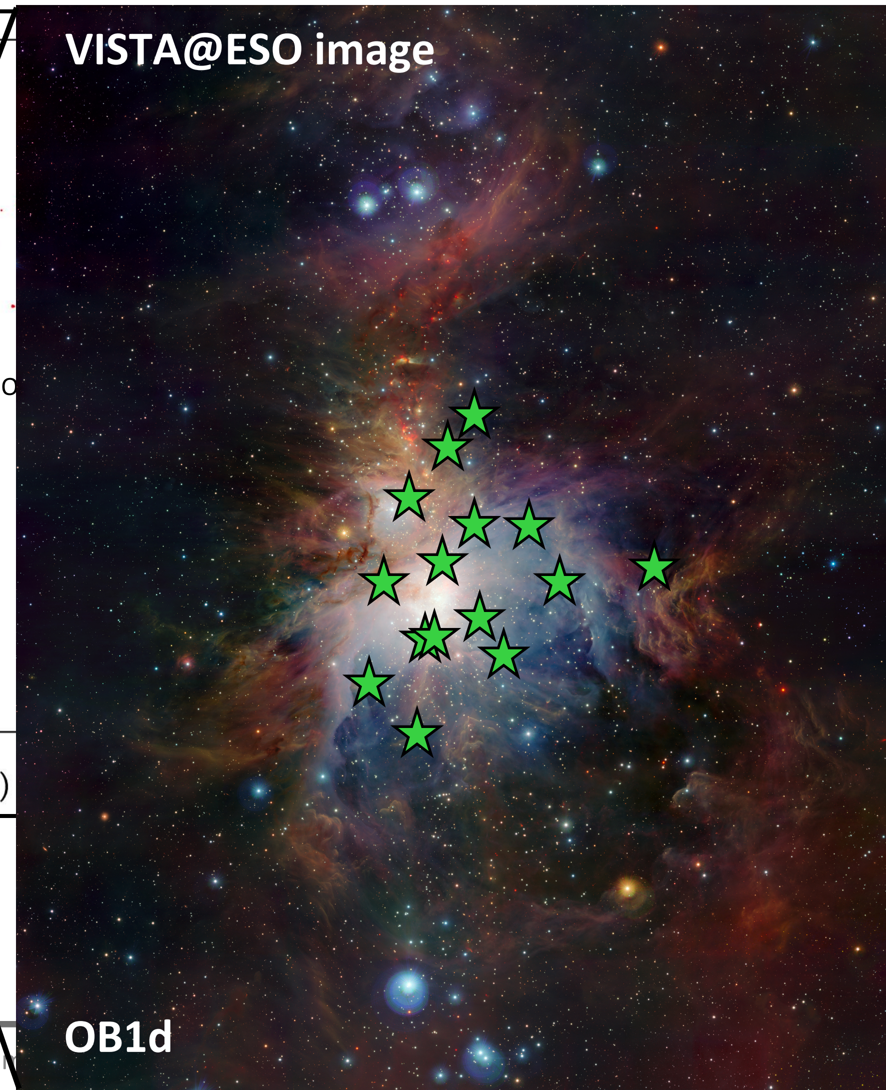
Orion boundaries (Warren & Hesser 1977)

	Age (Myr)	d (pc)	Reference
OB1a	7-10	350	Briceño et al. (2005)
OB1b	4-6	400	Briceño et al. (2007)
OB1c	2-6	400	Bally (2008)
OB1d	1-3	420	Da Rio et al. (2010)
25 Ori	7-10	330	Briceño et al. (2005)
λ Ori	5-10	400	Dolan & Mathieu (2002)

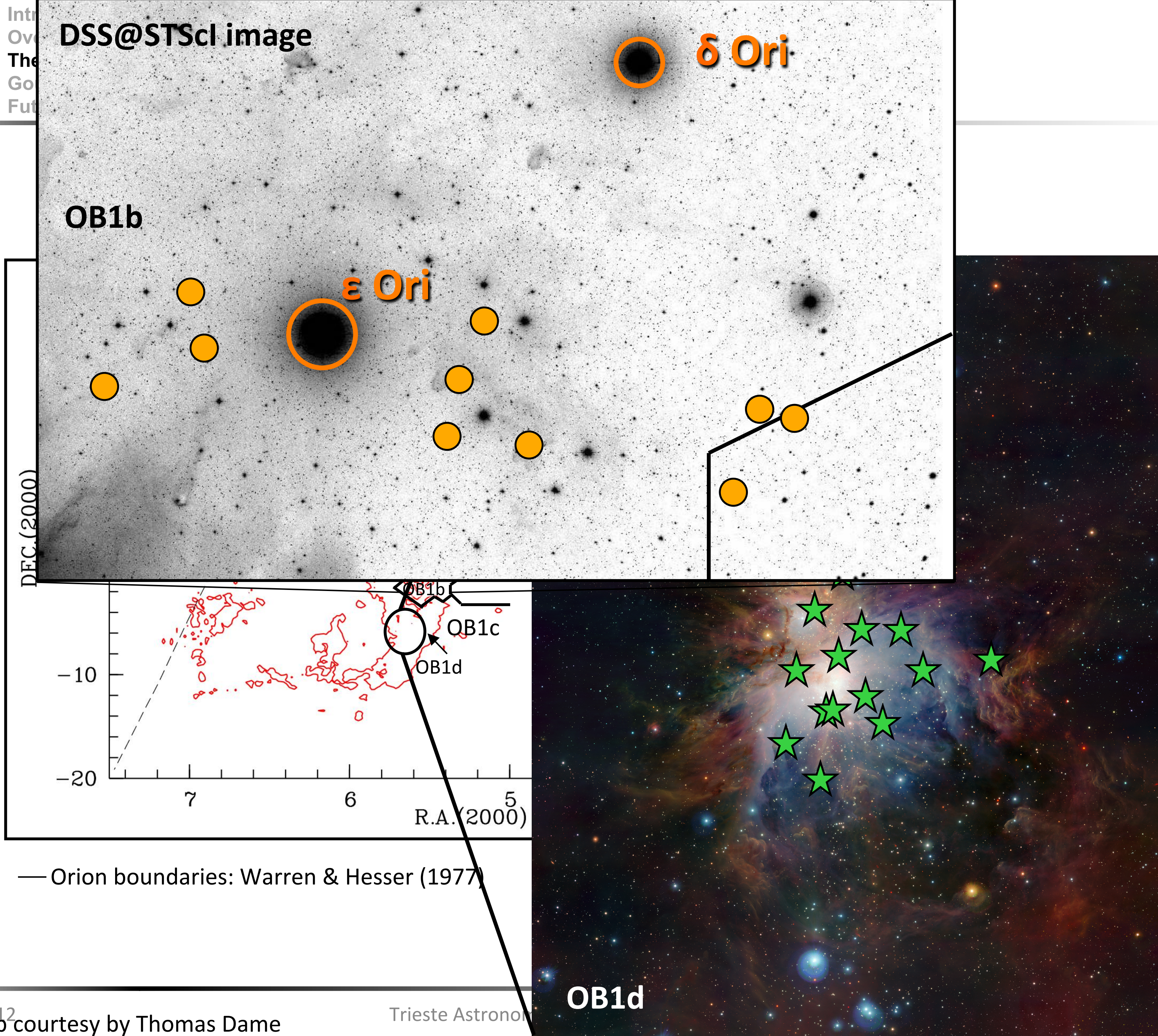
Properties and position



— Orion boundaries: Warren & Hesser (1977)

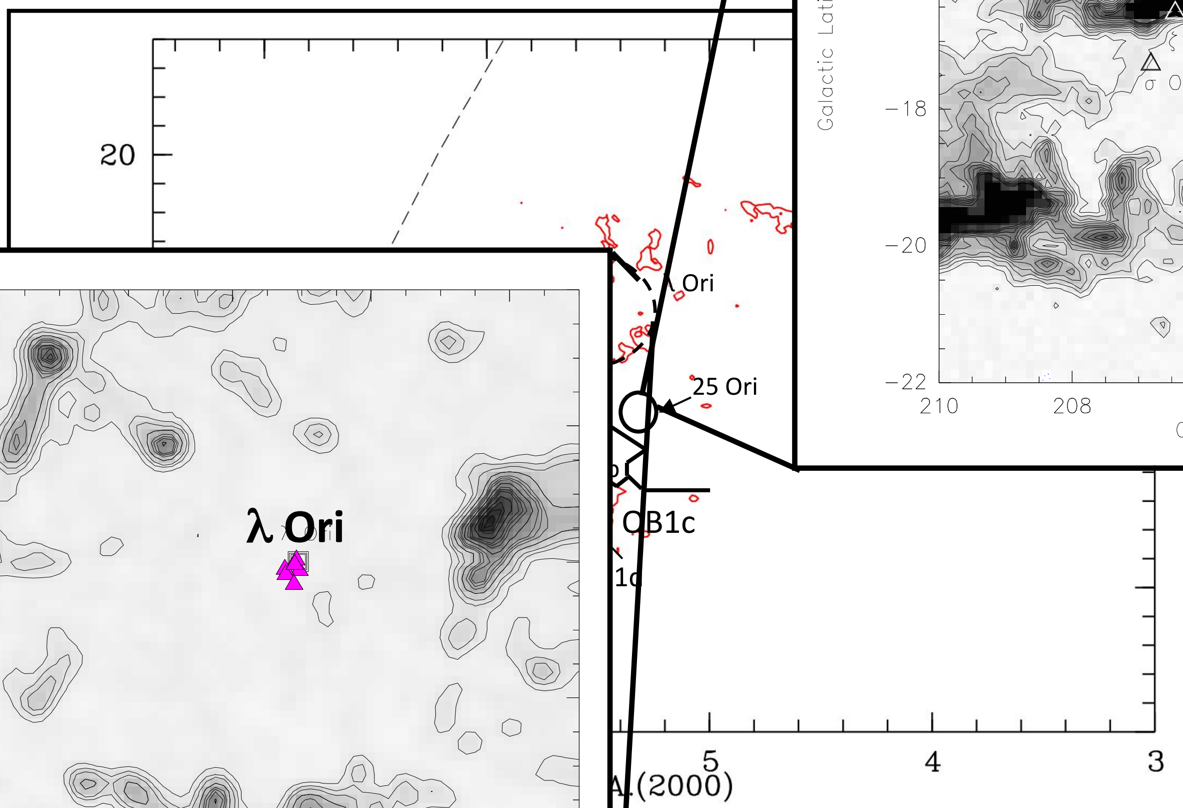


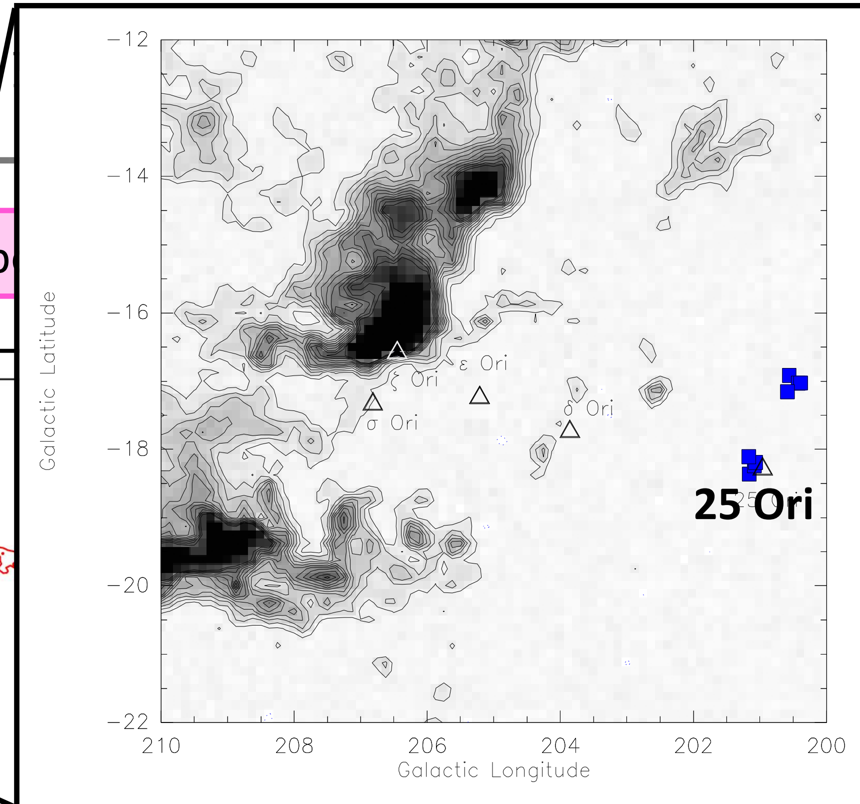
CO J=1→0 map courtesy by Thomas Dame

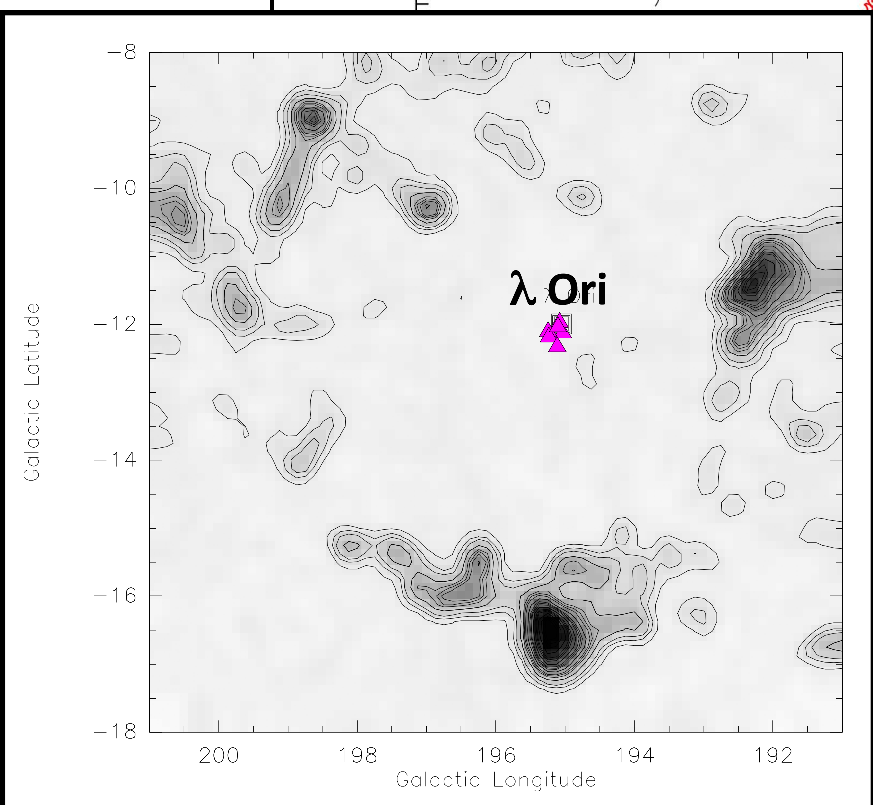


CO J=1→0 map courtesy by Thomas Dame

Properties and p







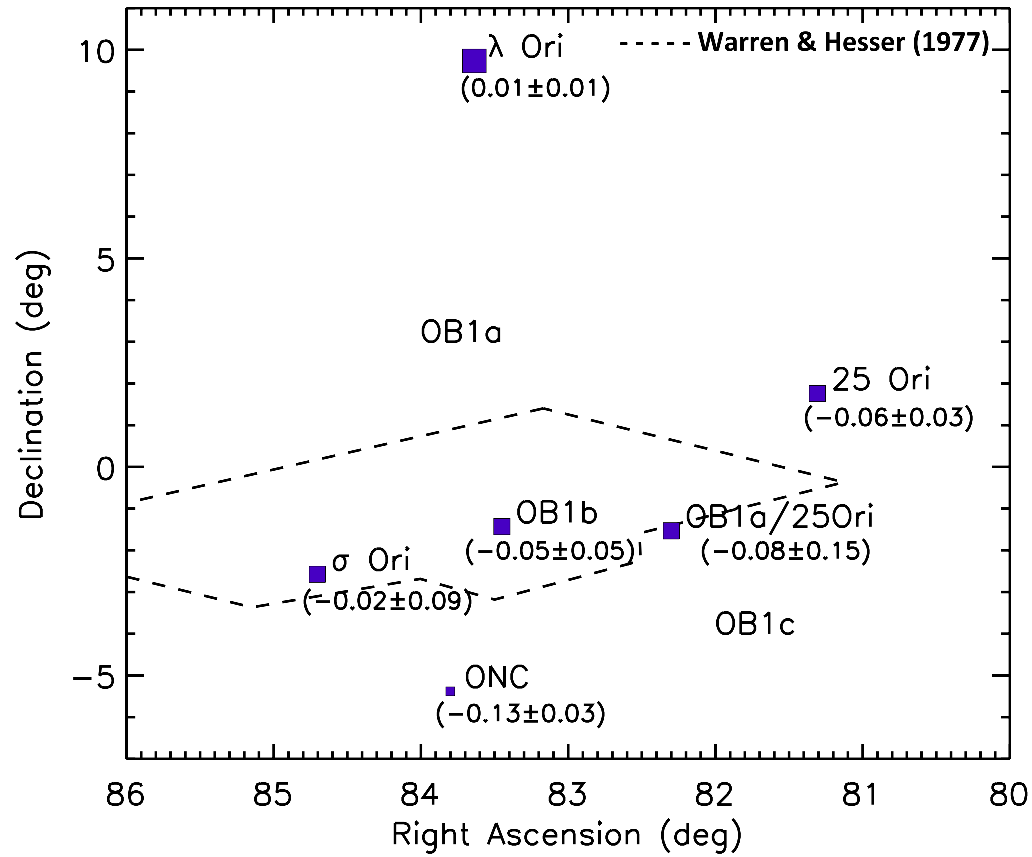
Biazzo et al. (2011a,b)

CO J=1→0 map courtesy by Thomas Dame

Iron abundance

Characteristics:
- ❑ Orion OB sub-groups homogeneous, with the exception of the ONC
- ❑ The youngest sub-group has the lowest [Fe/H]
- ❑ No evident contamination (in iron) between adjacent regions

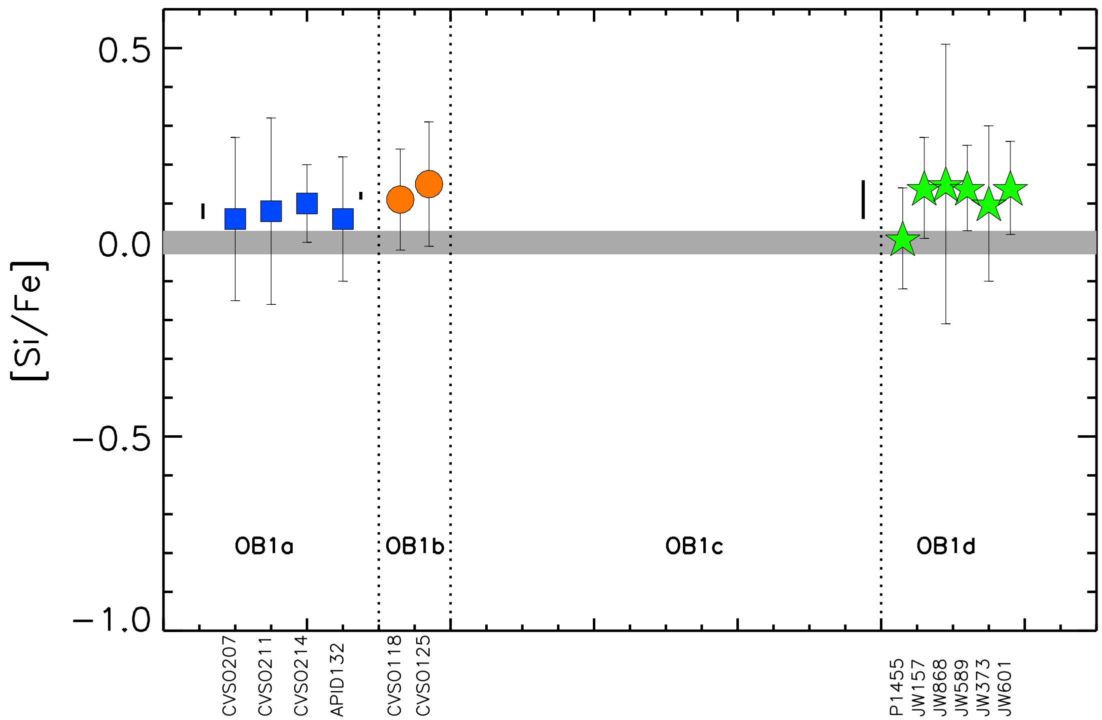
Reasons:
- ❑ Different and independent episodes of star formation (λ Ori/ other sub-groups)
- ❑ Large-scale formation process on ~1 kpc → not well mixed gas (Elmegreen 1998)



KB et al. (2011b)

Slight iron inhomogeneity in the Orion complex

Chemical self-enrichment in Orion?



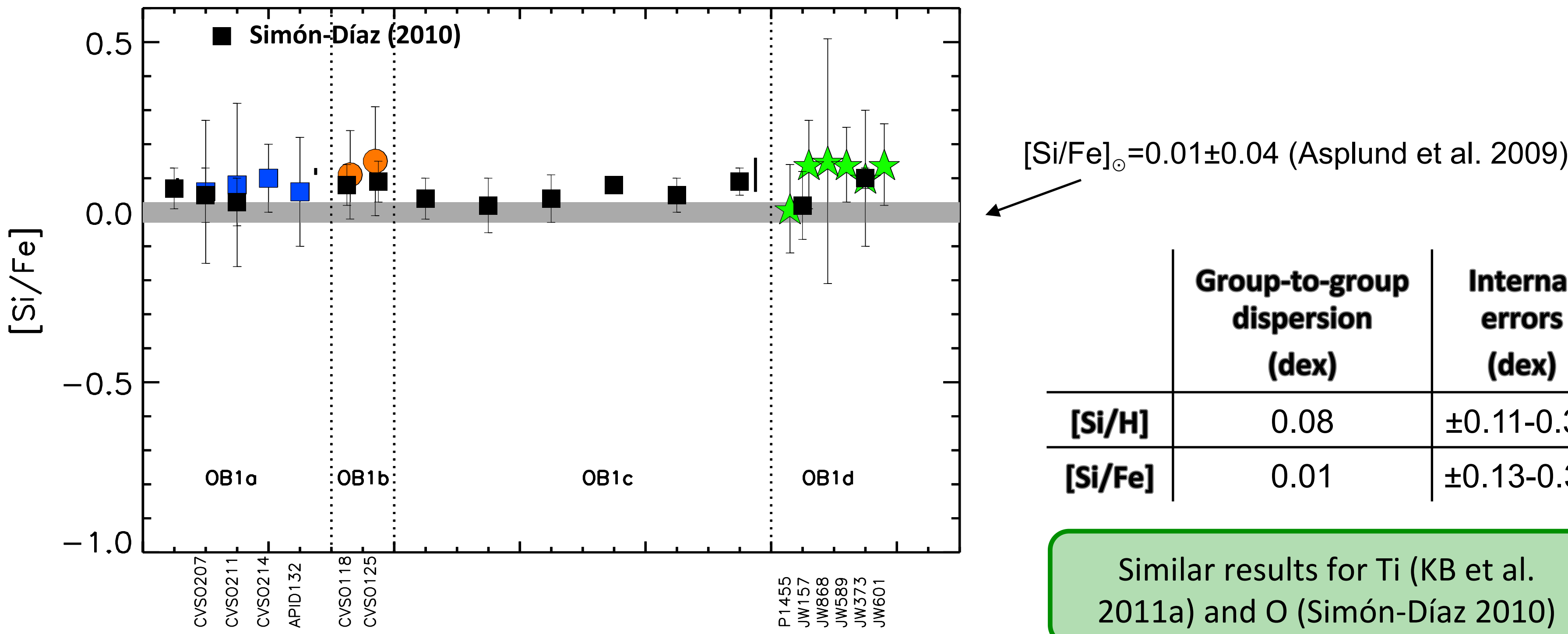
$[Si/Fe]_{\odot}$=0.01±0.04 (Asplund et al. 2009)

	Group-to-group dispersion (dex)	Internal errors (dex)
[Si/H]	0.08	±0.11-0.31
[Si/Fe]	0.01	±0.13-0.36

Similar results for Ti (KB et al. 2011a) and O (Simón-Díaz 2010)

No enrichment within the Orion sub-groups

Chemical self-enrichment in Orion?

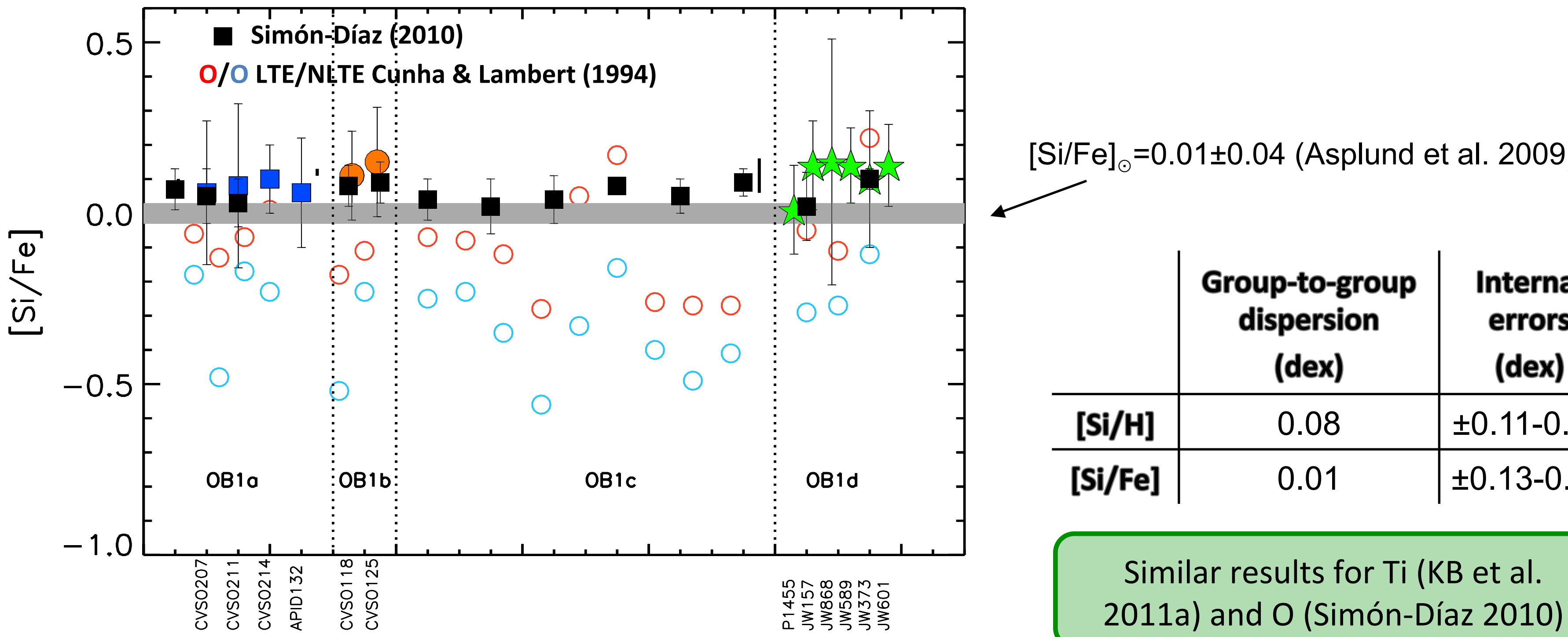


	Group-to-group dispersion (dex)	Internal errors (dex)
[Si/H]	0.08	±0.11-0.31
[Si/Fe]	0.01	±0.13-0.36

Similar results for Ti (KB et al. 2011a) and O (Simón-Díaz 2010)

No enrichment within the Orion sub-groups

Chemical self-enrichment in Orion?



	Group-to-group dispersion (dex)	Internal errors (dex)
[Si/H]	0.08	±0.11-0.31
[Si/Fe]	0.01	±0.13-0.36

Similar results for Ti (KB et al. 2011a) and O (Simón-Díaz 2010)

No enrichment within the Orion sub-groups

Iron abundance distribution of young populations

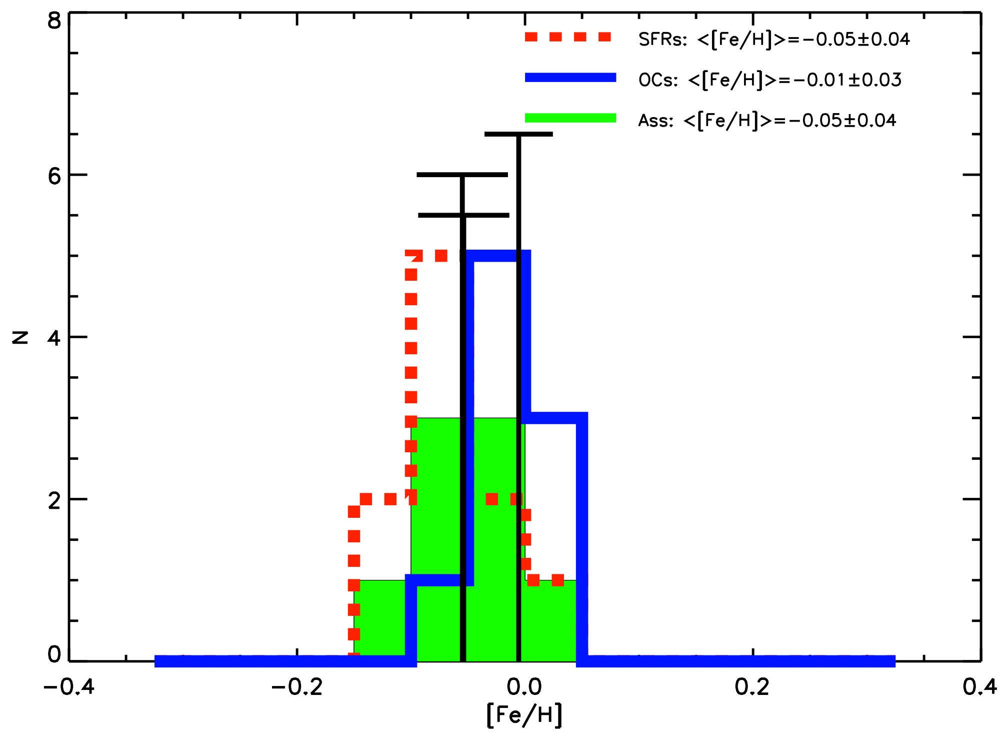
KB et al. (2011a)

Comparison at d < 500 pc:

- ❑ Star-Forming Regions
- ❑ Open Clusters younger than 150 Myr
- ❑ Moving groups (MG)

Characteristics:

- ❑ Low dispersion
- ❑ None of the OCs is metal-poor as SFRs/MGs

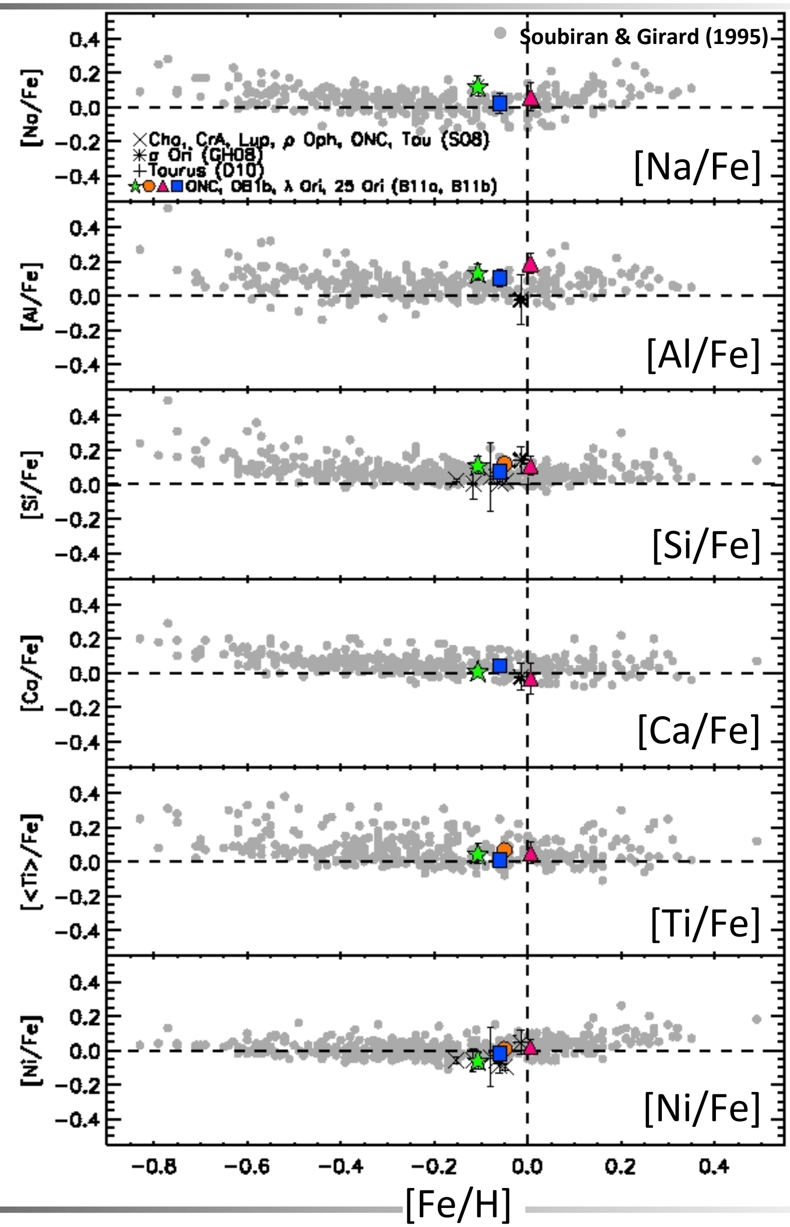


Different star-formation process/history in the solar vicinity

Young groups in the Galactic disk

- α-elements
- Iron-peak elements
- Sodium and Aluminium

Consistency with the thin Galactic disk



KB et al. (2011b)

Planet scenario

Main evidence:
Probability of hosting giant planets increases with the stellar [Fe/H] (Santos et al. 2004; Fischer & Valenti 2005; Johnson et al. 2010)

Caveats:
- ❑ Giants hosting planets do not appear more metal-rich than giants without planets (Pasquini et al. 2007)
- ❑ Correlation no longer valid for −0.7<[Fe/H]<−0.3 (Haywood 2009)

Planet scenario

Main evidence:
Probability of hosting giant planets increases with the stellar [Fe/H] (Santos et al. 2004; Fischer & Valenti 2005; Johnson et al. 2010)

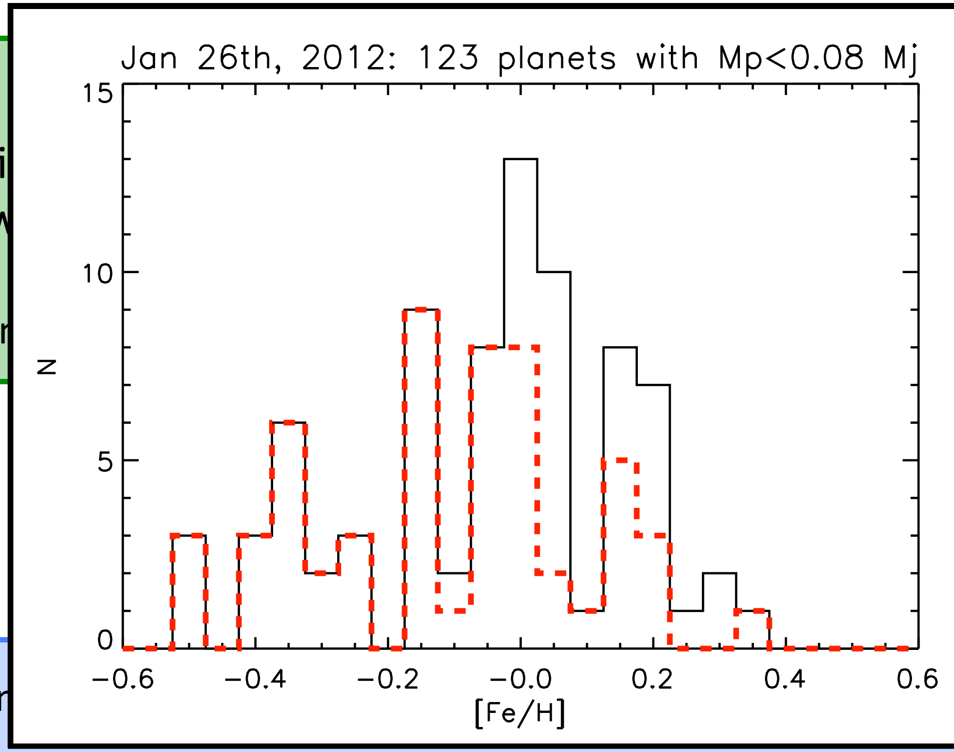
Caveats:
- ❑ Giants hosting planets do not appear more metal-rich than giants without planets (Pasquini et al. 2007)
- ❑ Correlation no longer valid for $-0.7<[Fe/H]<-0.3$ (Haywood 2009)

Do young stars with super-solar metallicity exist?

Metal-rich stars could have formed in the inner Galaxy and then suffered radial migration (Haywood 2008)

Planet scenario

Main evidence:
Probability of hosti
planets increases w
[Fe/H] (Santos et al.
Valenti 2005; Johnson



g planets do not
etal-rich than giants
(Pasquini et al. 2007)
o longer valid for
.3 (Haywood 2009)

?

Probability of findi
n in the inner disk…

❑ High metal content in the inner Galaxy can enhance the probability to form giant planets ⇒ **metallicity-dependent approach** (Mordasini et al. 2009)

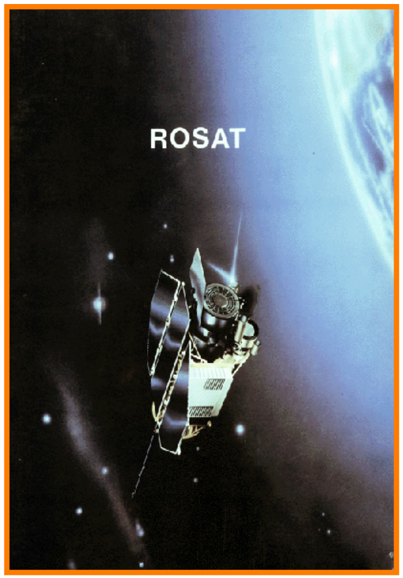
❑ Giant planet formation could be favoured in regions where H_2 is higher (molecular ring at 3-5 kpc) ⇒ **metallicity-indipendent approach** (Haywood 2009)

The Gould Belt in the Orion vicinity

The on-cloud population

The off-cloud population

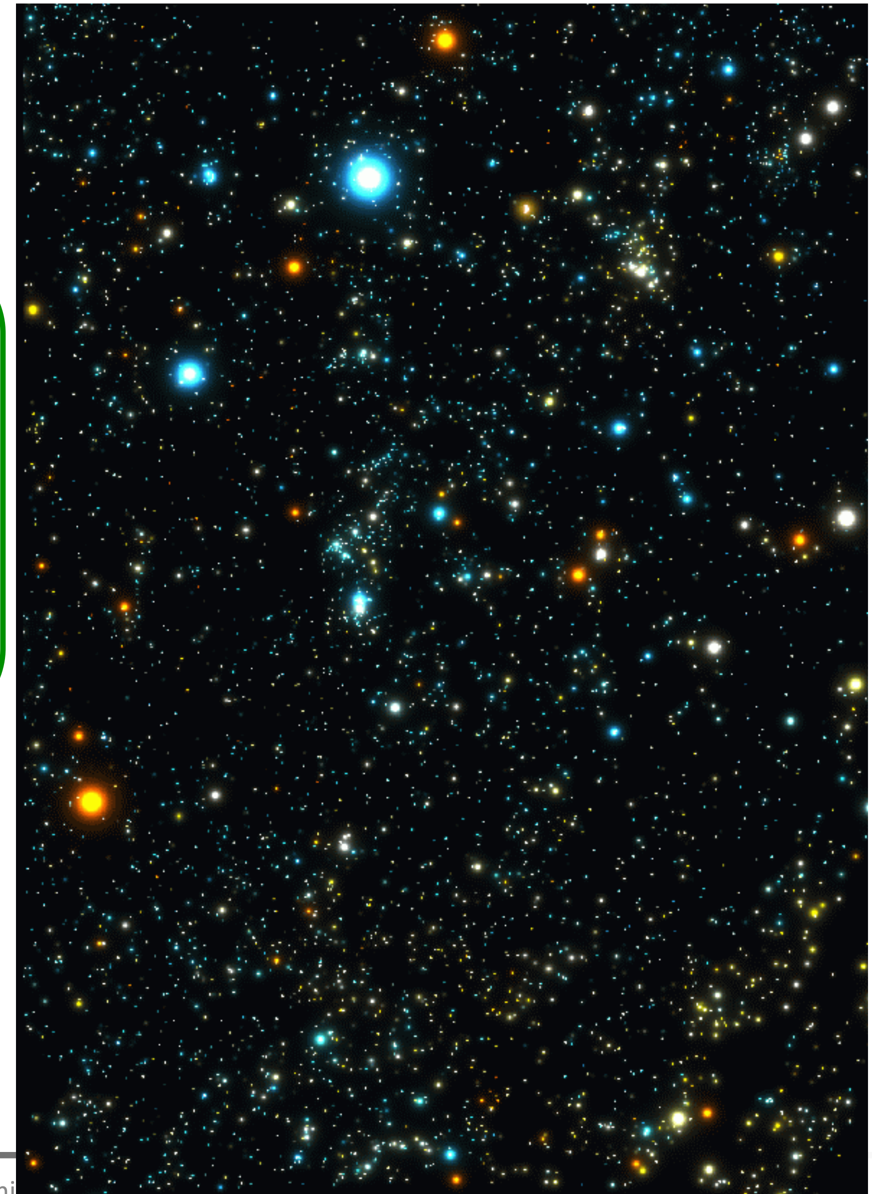
X-ray sky with ROSAT All-Sky Survey (RASS)



Spatially complete sample of X-ray sources

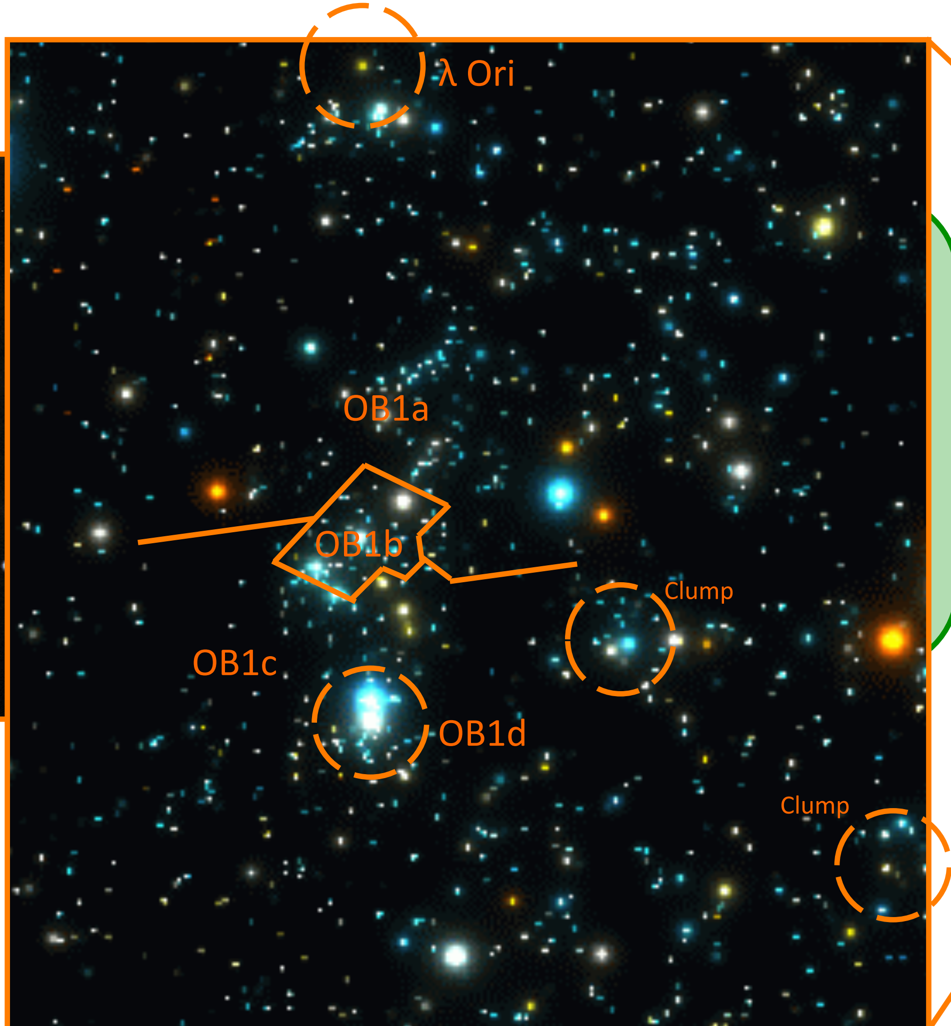
PSPC: 0.1-2.4 keV

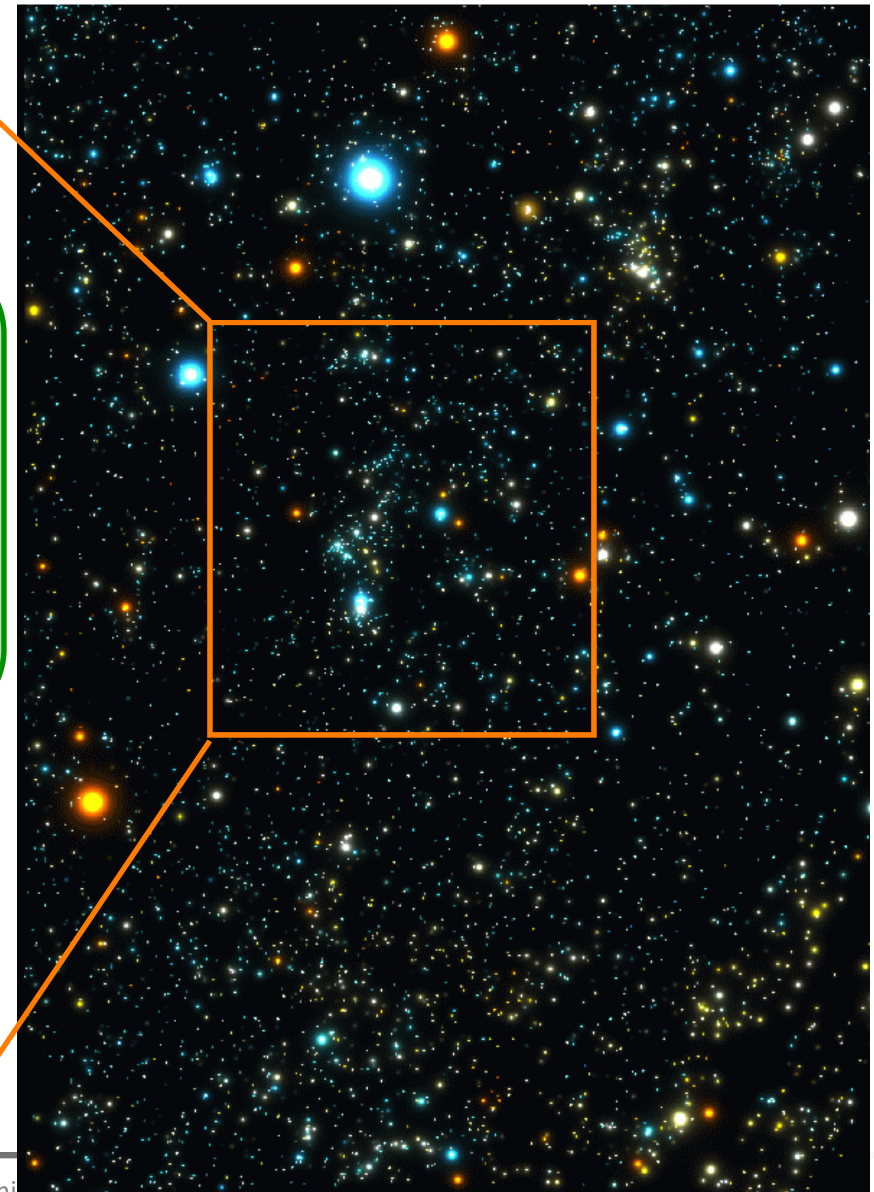
- ❑ $F_{Xlim} \sim 10^{-13}$ erg cm^{-2} s^{-1}
- ❑ $L_{Xlim}^{Orion} \sim 10^{30}$ erg s^{-1}



Credit: Alcalá

X-ray sky with ROSAT All-Sky Survey (RASS)



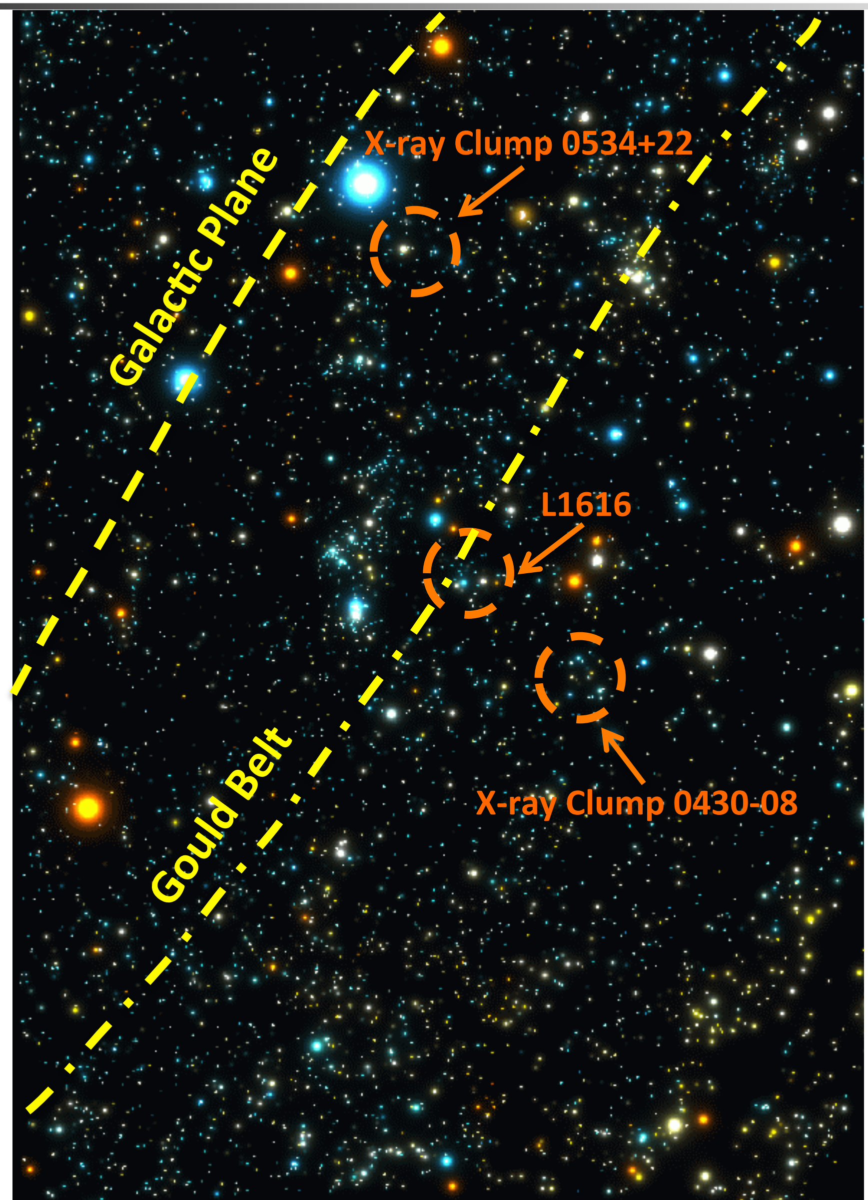


Credit: Alcalá

X-ray sky

RASS identification

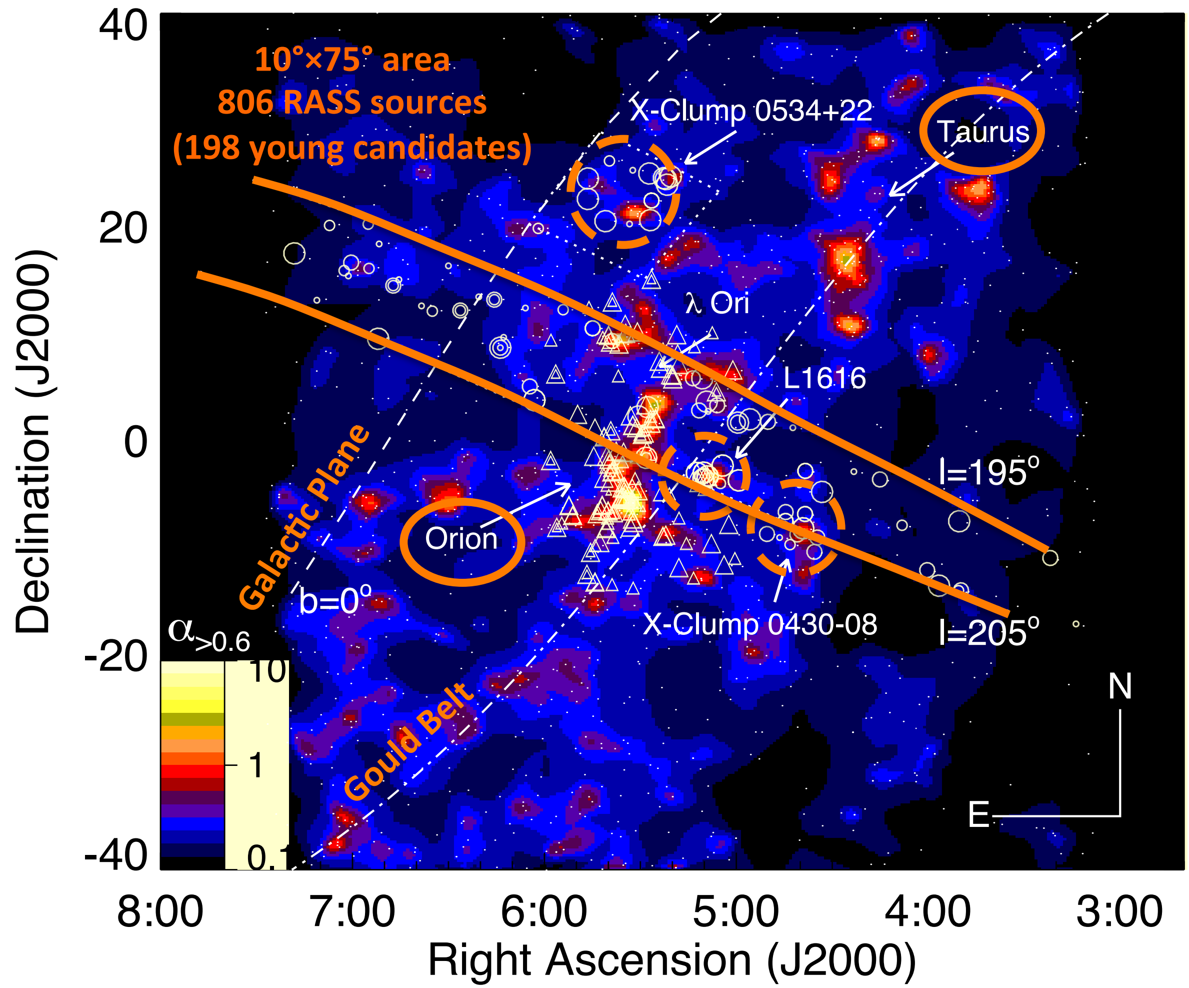
5000 deg^2 ⟶ 6482 sources



Crossing the Gould Belt…
Space-density map

Sterzik et al. (1995) X-ray selection criteria
(in a 60° × 80° area)

- 1483 young candidates
- Local enhancements
- Connection between Orion and Taurus by a broad lane following the disk-like structure of the GB
- The surface density drops down to 0.1 star/deg^2 near b_{II}=0° and at high b_{II}



KB, Alcalá et al. (2012)

Crossing the Gould Belt…
Spatial position

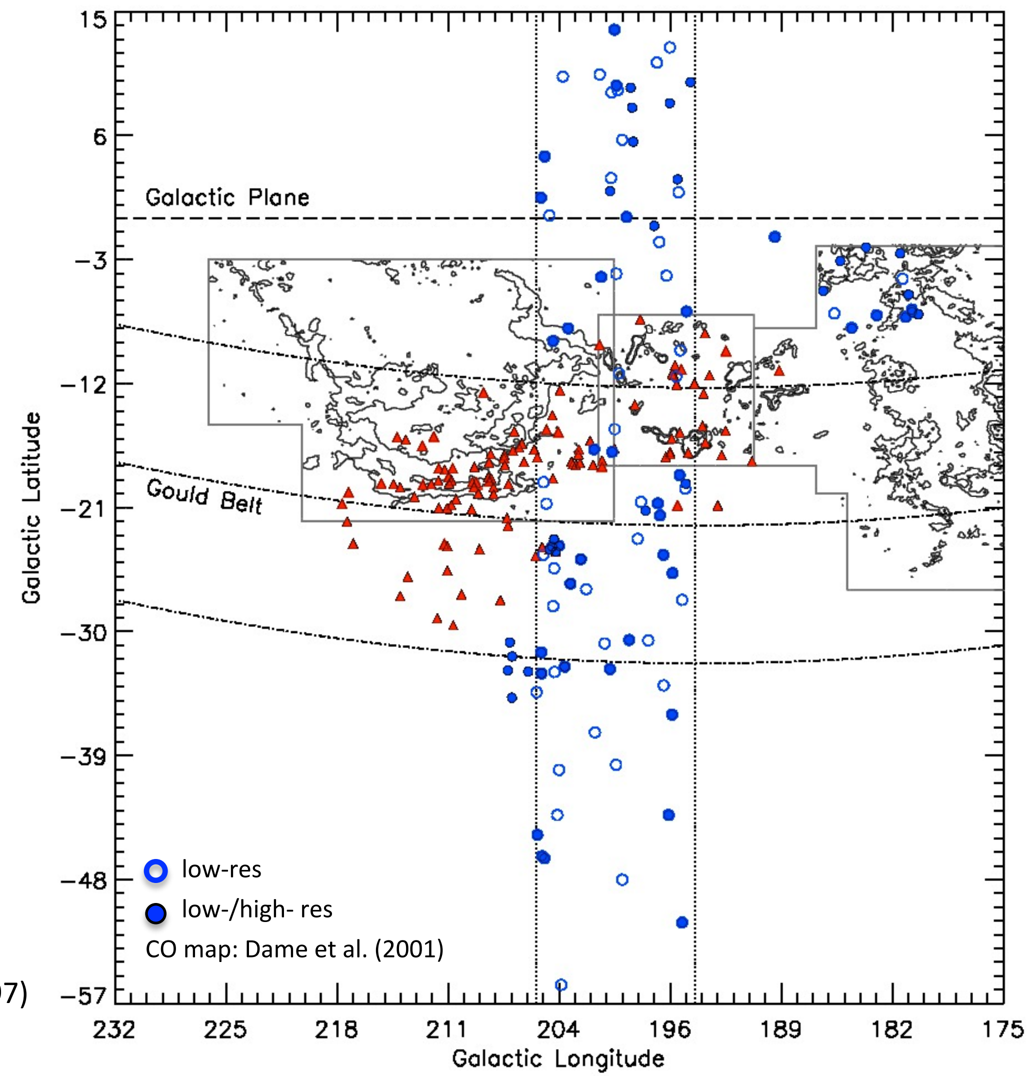
KB, Alcalá et al. (2012)

Spectroscopic identification

- **Observations** (203 stars):
  - Strip+Clumps (dots): 91 stars observed at low-resolution (B&Ch@ESO and OAN-SPM, R≈1600) and high-resolution (FOCES@CAHA, R=30000; FEROS@ESO, R=48000)
  - Widespread Region (triangles; Alcalá et al. 2000): 112 stars observed with FOCES@CAHA, CASPEC@ESO, CfA@Arizona (R=22000-35000)
- **Analysis**: SpT, Hα, T_{eff}, Li, V_{rad}, vsini, [Fe/H]

Previous spectroscopic identifications of RASS sources:

- Chamaeleon (Alcalá et al. 1995, 1997; Covino et al. 1997)
- Orion (Alcalá et al. 1996, 2000)
- Taurus-Auriga (Wichmann et al. 1996; Neuhäuser et al. 1997)
- Lupus (Krautter et al. 1997)
- Scorpius-Centaurus (Preibisch et al. 1998)



Crossing the Gould Belt…
Spatial position

KB, Alcalá et al. (2012)

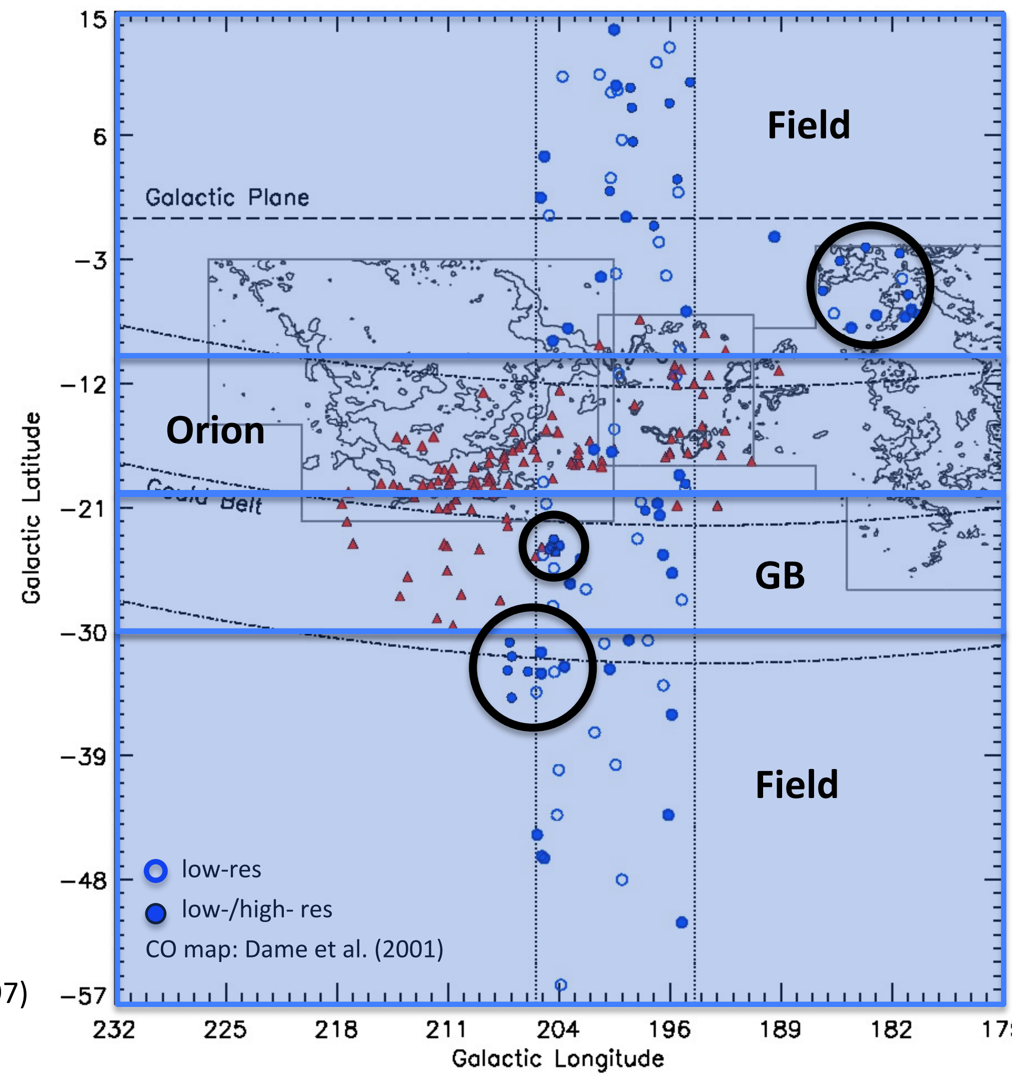
Spectroscopic identification
Some characteristics

SpT
- late-F/early-M stars

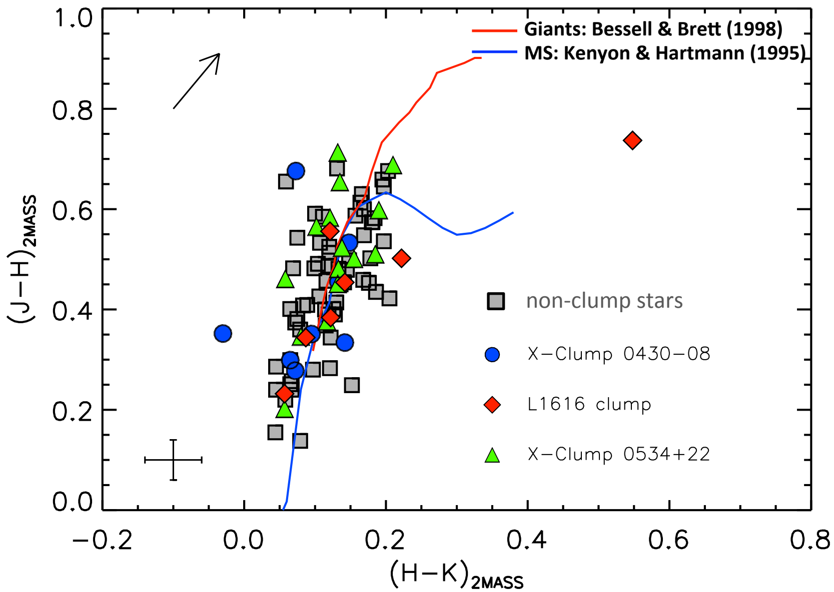
V_{rad}
- 'Field stars' ($b_{II}<-30°$, $-10<b_{II}<15°$): wide distr.
- 'Orion stars' ($-20°<b_{II}<-10°$): Orion distr.
- 'GB stars' ($-30°<b_{II}<-20°$) & Clumps: Orion/Taurus distr.

Previous spectroscopic identifications of RASS sources:

- Chamaeleon (Alcalá et al. 1995, 1997; Covino et al. 1997)
- Orion (Alcalá et al. 1996, 2000)
- Taurus-Auriga (Wichmann et al. 1996; Neuhäuser et al. 1997)
- Lupus (Krautter et al. 1997)
- Scorpius-Centaurus (Preibisch et al. 1998)



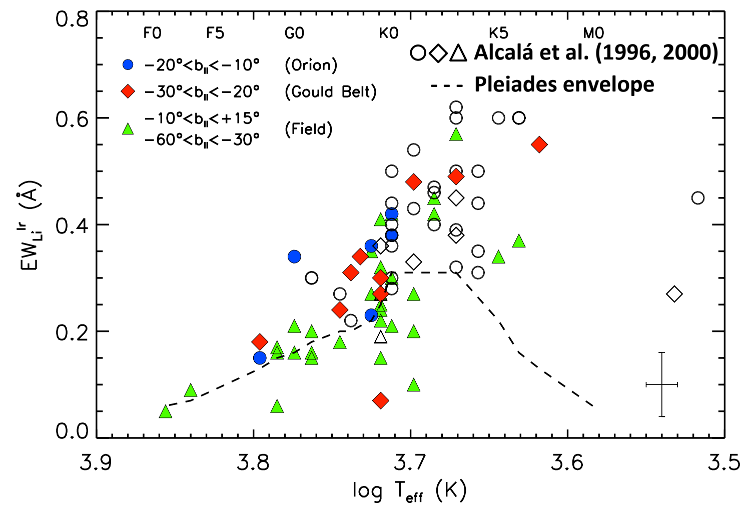
Strip & Clumps
NIR color-color diagram

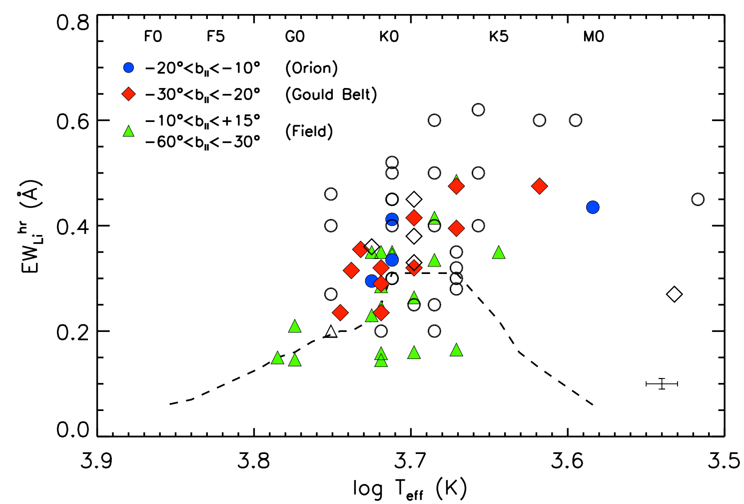


No NIR excess

- Orion ⟶ above the Pleiades env.
- GB ⟶ close to the Pleiades env.
- Field ⟶ spread

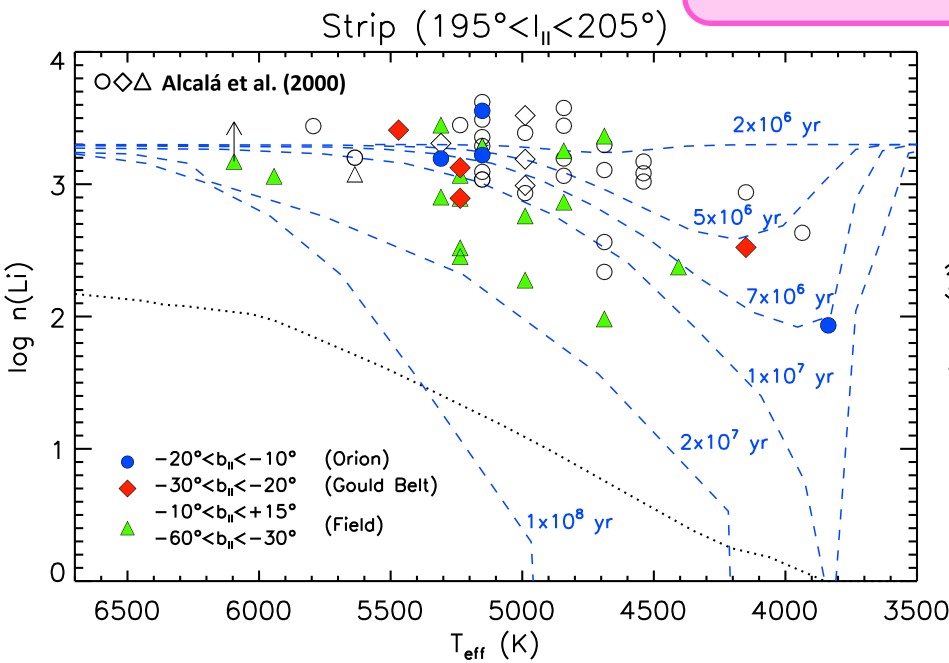
Strip & Clumps
Lithium detection

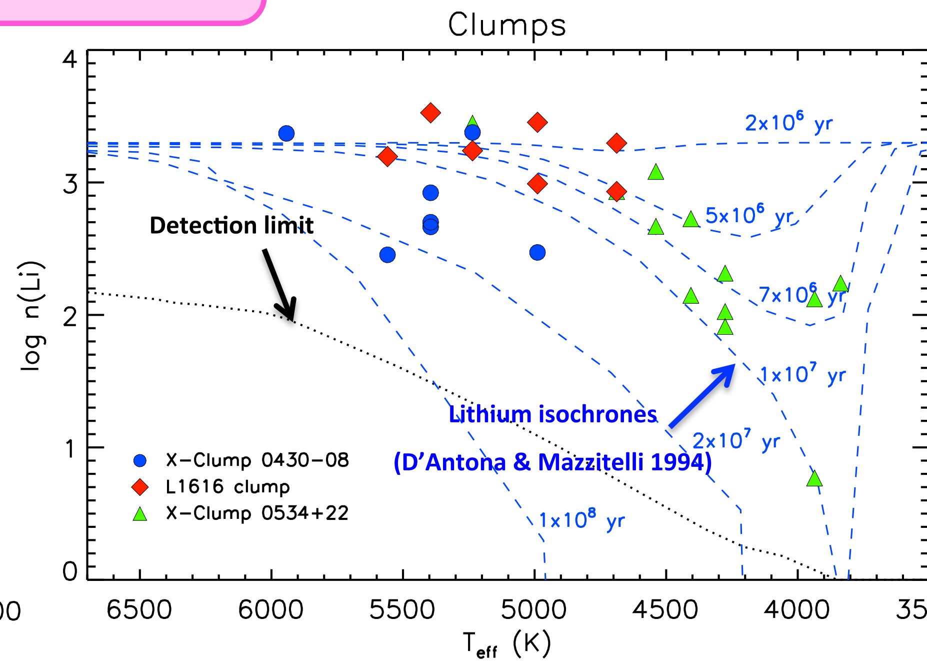




KB, Alcalá et al. (2012)

Strip & Clumps
Lithium abundance



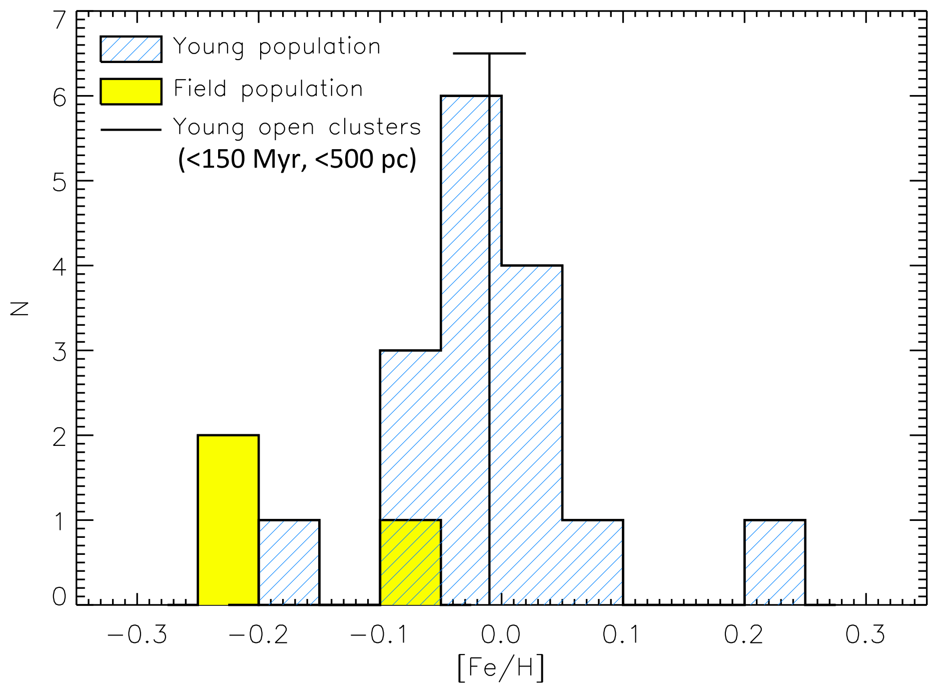


- ❑ Orion ⟶ ≈2-7 Myr
- ❑ GB ⟶ ≈5-10 Myr
- ❑ Field ⟶ spread

- ❑ X-Clump 0430-08 ⟶ ≈2-20 Myr
- ❑ L1616 ⟶ ≈2-7 Myr
- ❑ X-Clump 0534+22 ⟶ ≈2-10 Myr

KB, Alcalá et al. (2012)

Strip & Clumps
Iron abundance



Summarizing…

- ❑ **6482** RASS X-ray sources
- ❑ **1483** young stellar candidates
- ❑ **203** stars observed spectroscopically
- ❑ **19** stars suitable for iron abundance measurements!

- ❑ Young stars ≈ $[Fe/H]_{young\ Open\ Clusters}$=−0.01±0.03 (Biazzo et al. 2011a)
- ❑ Field (few) stars ≈ $[Fe/H]_{field\ nearby\ stars}$=−0.10±0.24 (Santos et al. 2008)

KB, Alcalá et al. (2012)

RASS and Galactic Model

How many X-ray active stars are expected?

Number of X-ray sources predicted with a Galactic Model (Guillout et al. 1996)

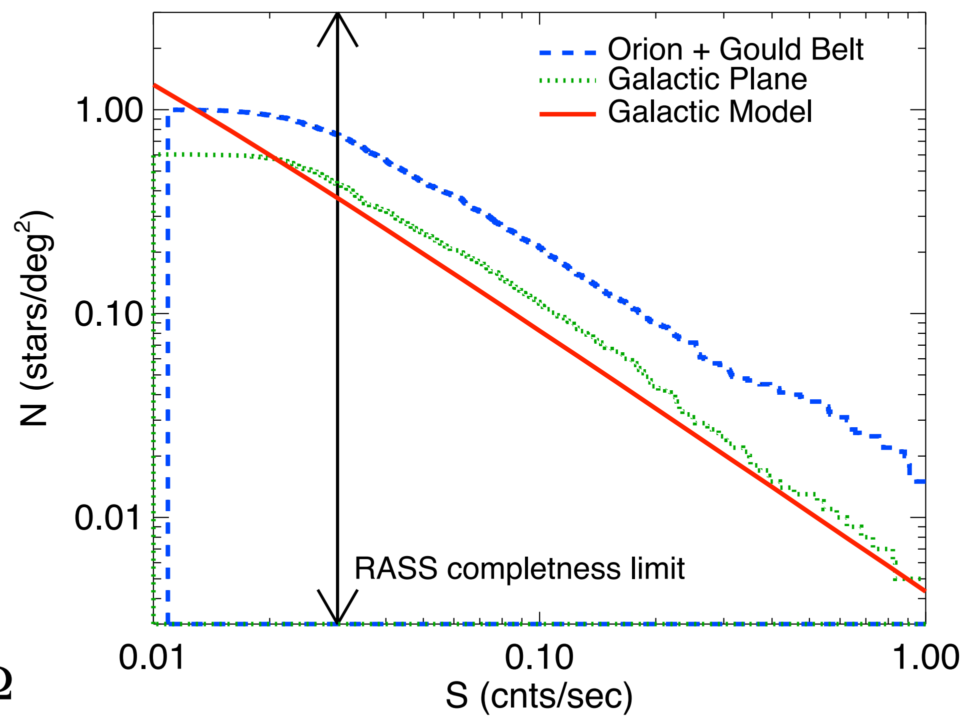
$$N(>S,l,b)=\sum_s\sum_a N_{sa}(>S,l,b)$$

S: count rate
l: galactic longitude
b: galactic latitude
s: spectral type
a: age

$$N_{sa}(>S,l,b)=\int_{L_{min}}^{L_{max}} F_{sa}(L_X)dL_X\int_0^{d_{max}}\rho_{sa}(r,l,b)r^2 dr d\Omega$$

$F(L_X)$: X-ray luminosity function
ρ: spatial density
r: distance
$d\Omega$: solid angle

KB, Alcalá et al. (2012)

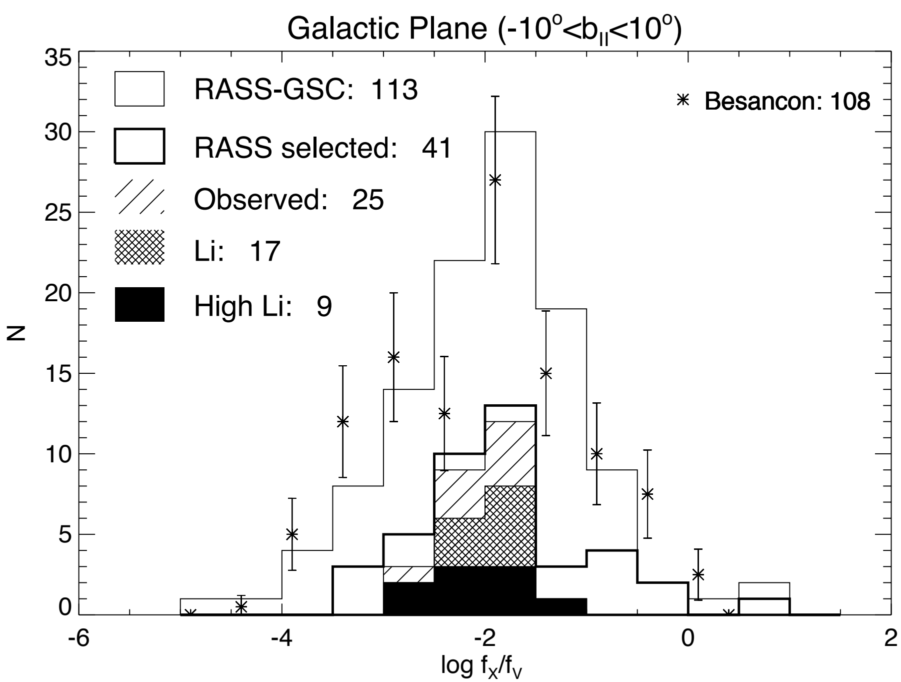


- Galactic Model consistent in the Galactic Plane region
- Source excess in the Orion+GB field

RASS, Galactic Model, and Spectroscopy *Strip*

Cumulative histograms:
(Δl_{II}=20°)

- −10°<b_{II}<+10°
- −20°<b_{II}<−10°
- −30°<b_{II}<−20°



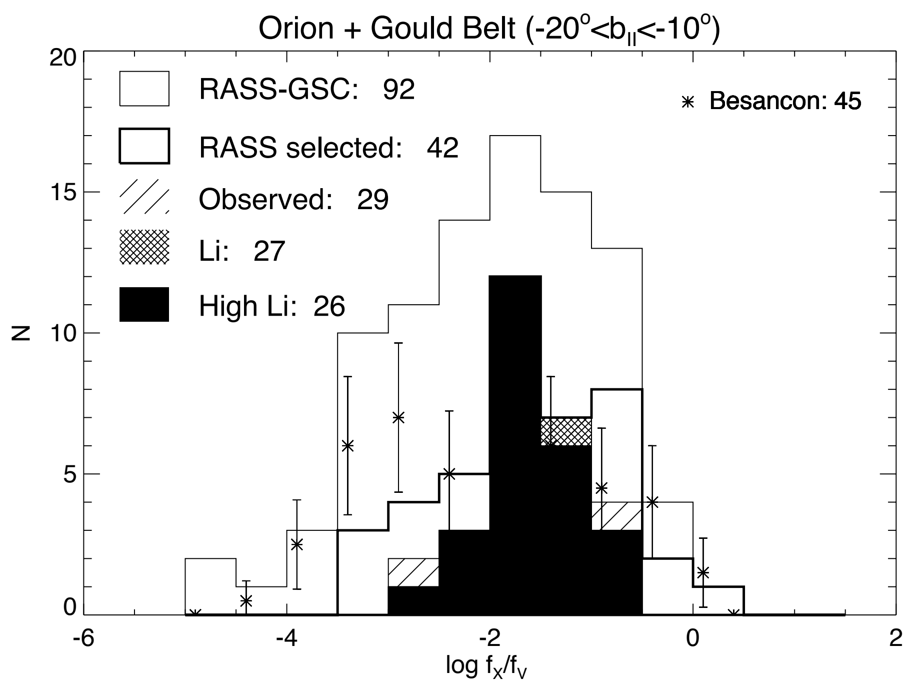
KB, Alcalá et al. (2012)

- RASS data and Galactic Model in agreement
- High-Lithium sources ≈ 1/3 observed stars

RASS, Galactic Model, and Spectroscopy
Strip

Cumulative histograms:
(Δl_{II}=20°)

- ❑ $-10° < b_{II} < +10°$
- ❑ $-20° < b_{II} < -10°$
- ❑ $-30° < b_{II} < -20°$



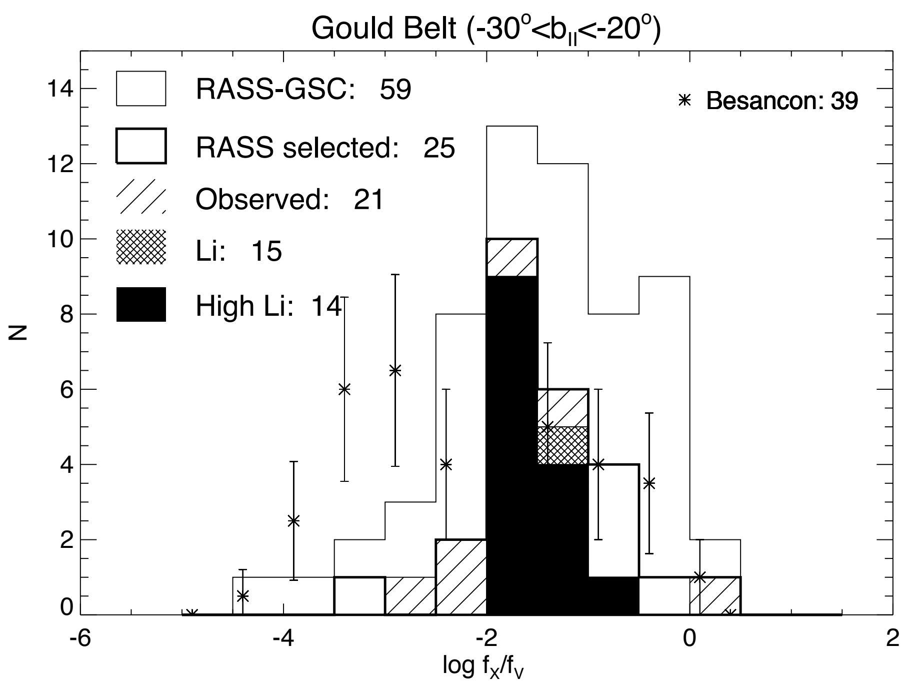
KB, Alcalá et al. (2012)

- ❑ Large RASS source excess (≈100%)
- ❑ High-Lithium sources ≈ 9/10 observed stars

RASS, Galactic Model, and Spectroscopy
Strip

Cumulative histograms:
(Δl_{II}=20°)

- ❑ $-10° < b_{II} < +10°$
- ❑ $-20° < b_{II} < -10°$
- ❑ $-30° < b_{II} < -20°$



KB, Alcalá et al. (2012)

- ❑ RASS source excess (≈50%)
- ❑ High-Lithium sources ≈ 2/3 observed stars

CONCLUDING…

- ❑ **Clustered population** (≥5-10 stars/deg², Very High-Li stars, # counts in strong excess, ≈Myr) ⟶ **Star-Forming Regions**
- ❑ **Dispersed young population** (0.5-5 stars/deg², High-Li stars, # counts in excess, <20 Myr) ⟶ **Gould Belt/Disk**
- ❑ **Widespread population** (0.5≤ stars/deg², ZAMS Li stars, # counts compatible with Galactic Model, >20 Myr) ⟶ **Field**

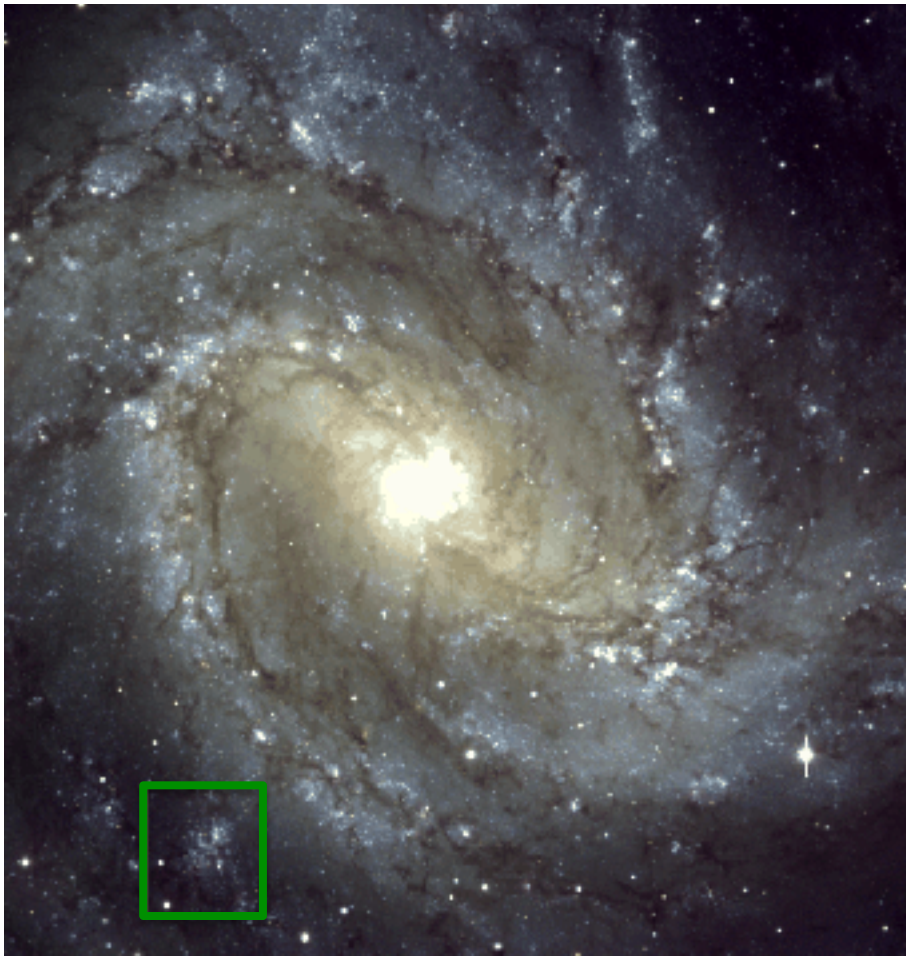
InfraRed

- **Gould Belt Spitzer Legacy Survey** (PI: Allen). Instruments: IRAC/MIPS (3-160 μm)
- **Herschel Gould Belt Survey** (PI: André). Instruments: SPIRE/ PACS (60-700 μm)
- **JCMT Gould Belt Legacy Survey** (PI: Ward-Thompson). Instruments: SCUBA-2/HARP/ POL-2 (200 μm-1mm)

Optical

- **RasTyc/RasHyp** follow-up (PI: Guillout). Spectrographs: ELODIE/ AURELIE@OHP, SARG@TNG
- **SACY** project (PI: Torres). Spectrographs: FEROS@ESO, CORALIE@SET
- **Gaia-ESO Survey** (PI: Gilmore & Randich). Spectrographs: FLAMES/ UVES@VLT, FLAMES/ Giraffe@VLT

GB-like structures



The case of M83
(Comerón 2001)

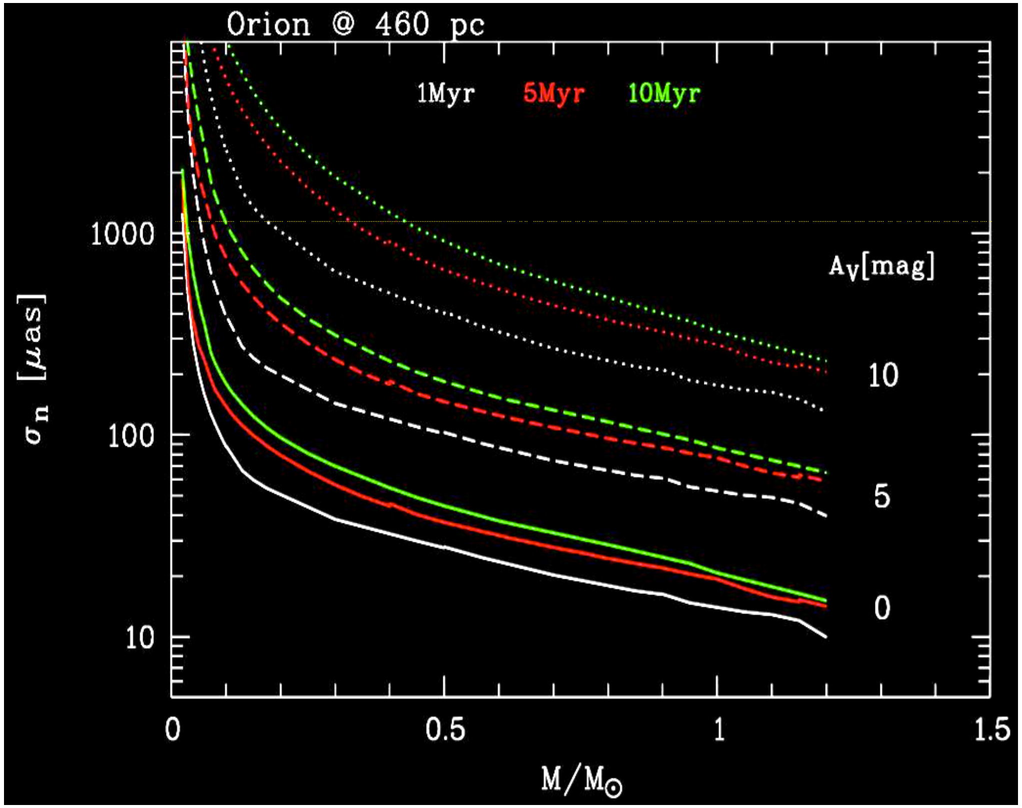
Similarities with the GB:
- ❑ Size
- ❑ Detachment from the spiral structure
- ❑ Age
- ❑ Integrated magnitude
- ❑ Distance to the center

Other cases
- ❑ NGC6946: Larsen et al. (2002), Efremov et al. (2007)
- ❑ NGC4559: Soria et al. (2004)
- ❑ NGC4038/39: Bastian et al. (2006)

Gaia and ESPRESSO

Main constraints:

- π & ($\mu_\alpha \cos\delta$, μ_δ) for a few stars
- Few (giant) exo-planets in young (≈500 Myr) clusters



Credit: Alcalá

Thanks to Gaia:

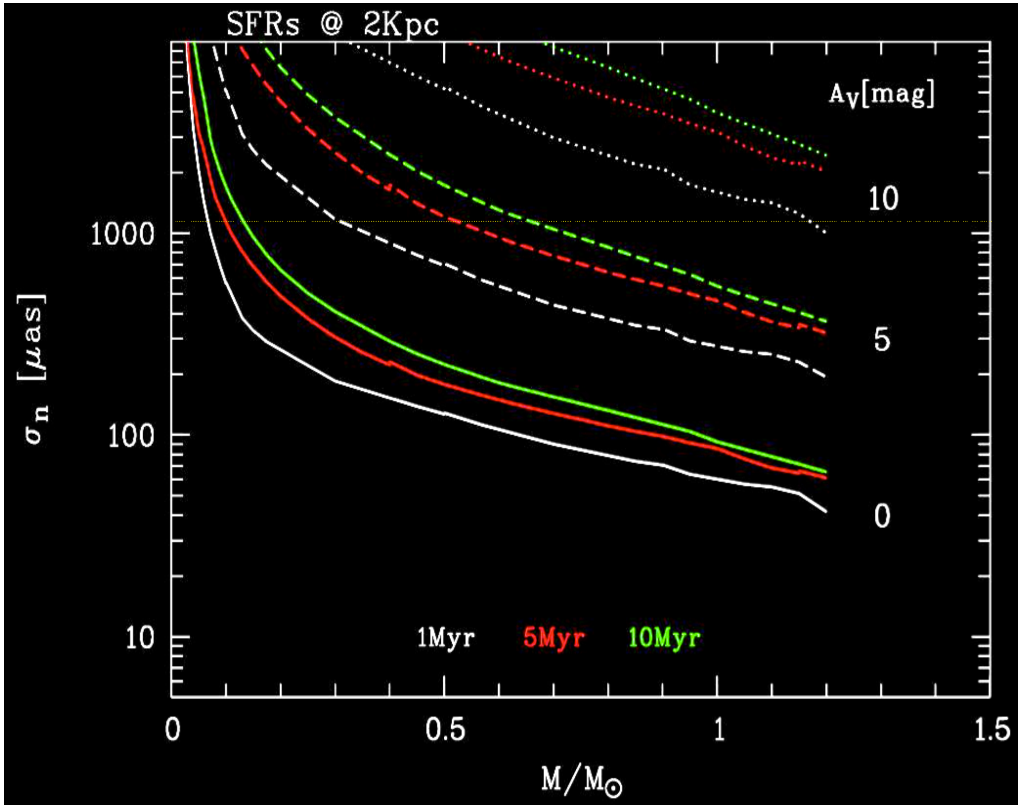
- For inner (<500 pc) GB: σ_π << 1 mas (A_V<10 mag) ⟶ distance errors of 1-7 pc @V=15-18 mag

Star-to-Star distances

Gaia and ESPRESSO

Main constraints:

- ❑ π & $(\mu_{\alpha} \cos\delta, \mu_{\delta})$ for a few stars
- ❑ Few (giant) exo-planets in young (≈500 Myr) clusters



Credit: Alcalá

Thanks to Gaia:

- ❑ For inner (<500 pc) GB: σ_{π} << 1 mas (A_V<10 mag) ⟶ distance errors of 1-7 pc @V=15-18 mag
  Star-to-Star distances
- ❑ At 2 kpc: σ_{π} < 1 mas (A_V<2 mag)

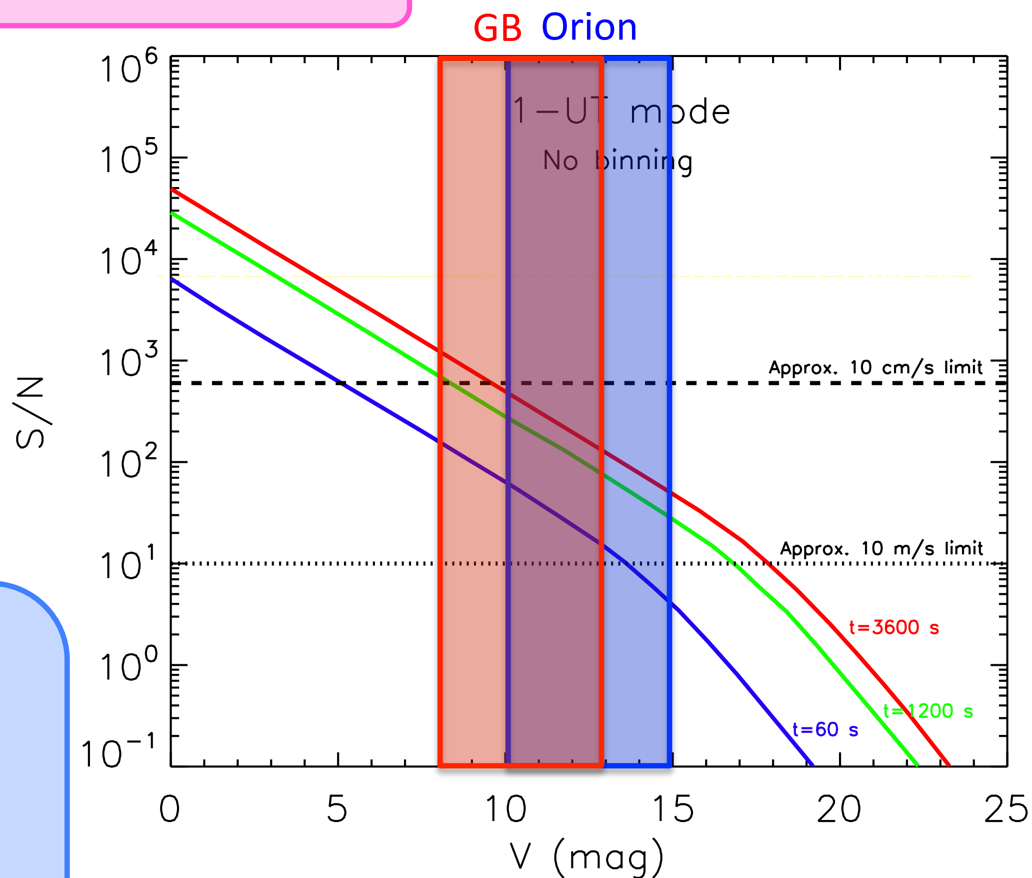
Gaia and ESPRESSO

Main constraints:

- π & ($\mu_\alpha \cos\delta$, μ_δ) for a few stars
- Few (giant) exo-planets in young (≈500 Myr) clusters

Thanks to ESPRESSO:

- 10<V<15 mag: 10 cm/s<σ_{Vrad} <10 m/s
  Giant Planets in young stars
- V<10 mag: σ_{Vrad} <10 cm/s
  Rocky Planets in young stars
- Abundance precision of ≈0.01-0.05 dex
- Connection with SPHERE



Pepe et al. (2010)

THANKS!